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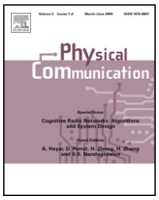

Full length article

Cyclostationary signatures for LTE Advanced and beyond

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ABSTRACT

Long Term Evolution (LTE) Advanced is the next generation of the LTE standard, offering peak data rates of up to 1 Gbps using up to 100 MHz of spectrum. A key mechanism in achieving this is carrier aggregation (CA) whereby multiple LTE component carriers (CCs) are combined in a contiguous or non-contiguous fashion. With the introduction of CA comes the challenge of network rendezvous. In order to associate with an LTE Advanced basestation or eNodeB, a User Equipment (UE) device must be capable of detecting component carriers in use by that eNodeB and establishing communications links. Looking beyond LTE Advanced, the introduction of service and technology neutral approaches to spectrum management is likely to increase the importance of rendezvous, as more diverse spectrum bands become available for use. This paper presents *cyclostationary signatures* as a powerful tool for overcoming the challenge of network rendezvous in LTE Advanced networks and beyond. A signature detector design, based on the Autocoherence Function (AF), is presented and a number of mechanisms for embedding signatures in downlink LTE CC waveforms are described. The performance of our signature detector is examined in depth through simulation under conditions of doubly-selective fading. Simulation results highlight the performance advantages which can be achieved through use of the AF-based detector over the simpler time-smoothed cyclic cross periodogram (TS-CCP)-based detector. Over the air experiments using a software radio based transceiver are described and results are presented.

1. Introduction

In order to meet the performance and technical requirements specified for fourth generation (4G) mobile systems, Long Term Evolution (LTE) Advanced standards offer improvements over preceding LTE standards, while supporting backward compatibility. Carrier aggregation (CA) is one of the key improvements in LTE Advanced, which allows the aggregation of two or more LTE carriers to increase the bandwidth for a single user equipment (UE) device up to 100 MHz [1]. Each individual carrier is called a component carrier (CC), which can support one of the bandwidth configurations ranging from 1.4 to 20 MHz. LTE Advanced allows both intra- and inter-band CA, where the CCs are located in the same band or different bands, respectively. In both cases, CCs aggregated within a band can be contiguous or non-contiguous. Despite its benefits, CA poses a number of technical challenges in practice. These challenges include the flexible use of a wide range of frequency bands, fast and robust detection of the CCs involved in CA by the UEs, and the design of control signalling, while being backward compatible with LTE systems. In this paper, we apply a tested mechanism for network coordination in dynamic spectrum access systems to the challenge of CA in LTE Advanced systems and beyond.

Initial specifications for LTE Advanced have identified a limited number of frequency bands for intra- and inter-

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band CA [2]. However, progression beyond LTE Advanced and the consideration of paradigms such as the opening up of the *TV white spaces* to secondary use [3] and the introduction of *technology and service neutral* use of the radio spectrum [4] promote the use of CA over a much wider range of frequency bands.

One of the biggest challenges in this case is *network rendezvous*, which requires the detection of individual CCs by the LTE Advanced UEs and establishment of the communications links on those carriers. In this paper, we propose embedding robust features into downlink frames on each CC to facilitate successful network rendezvous, at the expense of introducing only a small level of overhead in the downlink transmissions. These intentionally embedded features are called *cyclostationary signatures*. Previous work has shown that their use provides a powerful tool for achieving network rendezvous and coordination in reconfigurable wireless networks using multi-carrier waveforms, without any need for a static common control channel. Signatures can be used for signal detection, identification, carrier frequency acquisition and bandwidth estimation [5–9].

Our first contribution in this paper is to show how cyclostationary signatures can be embedded into LTE downlink frames. We introduce two different approaches. The first approach is fully compatible with the LTE physical downlink frame structure and requires minor changes in the LTE basestation (eNodeB) scheduler, whereas the latter approach results in some specific changes in the eNodeB scheduler and transmitter and the UE receivers but incurs less overhead. We describe a signature detector, based on the autocoherence function (AF), and present new simulation and experimental results to examine its performance under doubly-selective fading channels.

The remainder of the paper is organized as follows. Section 2 provides background information on cyclostationary signatures and their generation and presents the AF-based detector. The use of cyclostationary signatures to facilitate CA in LTE Advanced and beyond is addressed in Section 3. Simulation and experimental results are presented in Section 4 and the conclusions can be found in Section 5.

2. Cyclostationary signatures

A signal is cyclostationary if there exists some nonlinear transformation of that signal which will generate finite-strength additive sine-wave components [10]. A signal is said to exhibit *second-order* cyclostationarity if its mean and autocorrelation are periodic.

Many of the communications signals in use today exhibit second and higher-order cyclostationarity due to underlying periodicities introduced through coupling stationary message signals with periodic sinusoidal carriers, pilot sequences, spreading codes and repeating preambles. It has been shown that these cyclostationary properties can be used to achieve a number of critical tasks including signal detection [11], classification [12], synchronization [13,14] and equalization [15].

Cyclostationary signatures are features which are not inherent to a signal of interest but are rather intentionally embedded for a particular purpose. It has been shown that these signatures or watermarks provide an effective tool for achieving rendezvous and network coordination in dynamic spectrum access networks [7]. The key advantage of using embedded cyclostationary features is that they form a very low-level physical property of the signal. As such, they may be detected and analysed prior to time or frequency synchronization and with very little prior knowledge about the physical parameters of the signal.

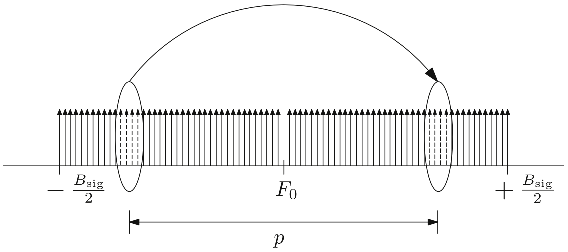

Fig. 1. Generation of a cyclostationary signature using OFDM subcarrier set mapping.

Intentionally embedded features provide a number of key advantages over the use of inherent signal features. Firstly, embedded features can be easily manipulated to suit the requirements of the system designer. With inherent features this is not typically possible without significantly changing the physical properties of the signal in question. Secondly, embedded features can be easily generated in the signal of interest and can be detected and analysed using low-complexity detector designs. Furthermore, embedded features can typically be detected using shorter observation times than those required for reliable detection of inherent features.

2.1. Signature generation

Cyclostationary signatures can be easily embedded in multicarrier waveforms through subcarrier mapping. This process involves the transmission of identical data symbols on two discrete sets of subcarriers and is illustrated in Fig. 1 for an Orthogonal Frequency Division Multiplex (OFDM) signal. Here, F_0 is the DC carrier, B_{sig} is the signal bandwidth and p is the subcarrier set separation.

OFDM signals may be represented as a composite of N statistically independent subchannel Quadrature Amplitude Modulated (QAM) signals [16]:

$$w(t) = \sum_k \sum_{n=0}^{N-1} \gamma_{n,k} e^{j(2\pi/T_s)nt} q(t-kT) \tag{1}$$

where $w(t)$ is the complex envelope of an OFDM signal with a cyclic prefix, $\gamma_{n,k}$ is the independent, identically distributed message symbol transmitted on subcarrier n during OFDM symbol k, N is the number of subcarriers and $q(t)$ is a square shaping pulse of duration T. T_s is the source symbol length and T_g is the cyclic prefix length such that $T = T_s + T_g$.

Subcarrier set mapping is carried out as:

$$\gamma_{n,k} = \gamma_{n+p,k}, \quad n \in M \tag{2}$$

where M is the set of subcarrier values to be mapped and p is the number of subcarriers between mapped symbols.