Cyclostationary signatures for cognitive radio applications and novel multiple access systems

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Abstract: This paper provides a theoretical discussion of two key and ongoing topics in wireless networks, namely spectrum availability and system capacity. Cognitive radio is the current state-of-the-art technology for tackling the former issue. Solutions for the latter topic are usually interference-limited or come at the cost of impractical computational complexity. The use of cyclostationary signatures for OFDM-based systems has recently been suggested to address the aforementioned research challenges.

1 Introduction.

The aim for future mobile systems is to support high user capacities and enhanced peak data rates targeting 100 Mbps for high and 1 Gbps for low mobility. Crucial performance metrics include bandwidth, spectral efficiency, latency, mobility and coverage. Another key requirement of next generation mobile networks is the seamless handover between different networks while maintaining compatibility with legacy architecture and existing security mechanisms. [1] Hence, academia and industry are heavily involved in developing novel tools and methods tackle the above issues.

The major concern in wireless networks is spectrum availability. Bandwidth is scarce and comes at a premium. Thus, there is a need for an efficient allocation and sharing of the available spectrum resources. As a result, one of the burning research topics in which many researchers are currently engaged in is Dynamic Spectrum Access (DSA). DSA exploits the existing wireless spectrum opportunistically which in turn is feasible via cognitive radio (CR) techniques. [2]

One of the key challenges in CR research is the detection of weak signals over a wide spectrum range. In addition, there is a trade-off between the complexity of the system, the speed at which it can sense and implement spectrum changes and the probability of error. [2] Although numerous different methods have been devised to deal with this challenge, this paper focuses on a recent innovative technique for the reliable detection of signals and selection of networks. This technique is based on the use of cyclostationary signatures, which exploit the inherent cyclostationarity embedded in the cyclic prefix of an OFDM signal. This is primarily due to the fact that future systems are likely to employ multicarrier channels by adopting Orthogonal Frequency Division Multiplexing (OFDM). [1]

Cyclostationary signatures for CR applications is a topic that has attracted the attention of many researchers across the globe. The use of these signatures though can be applied in a different research domain of equivalent importance, namely system capacity in cellular networks. The most practical way of improving user capacity is by decreasing the cell size; however, doing so leads to increased co-channel interference (CCI). Novel algorithms for boosting data rates have been proposed by several researchers but these usually come at the cost of impractical computational complexity. Hence, cyclostationary signatures are being investigated as a viable alternative to the previous solutions.

The remainder of this paper is organised in three parts. In the first part, we provide an overview of cognitive radio and the recent research work that has taken place in this domain. In the second part, we explore in detail the features and applications of cyclostationary signatures. In the third part, we investigate the potential of using such signatures for improving system capacity in mobile networks.

2. Cognitive radio.

Cognitive radio is based on the concept of software-defined radio. Software radios are totally programmable in terms of their channel access modes, channel modulation and other functionalities. Cognitive radio is used to sense the radio environment and change the transceiver parameters accordingly to make use of idle radio resources, known as spectrum holes. The higher the usage, the higher the spectral efficiency, which in turn depends on how well traffic load can be predicted to generate a swift and accurate reconfiguration of the system. [2]

In a recently co-authored paper [3], we bring together theory from the cognitive radio and machine learning domains to introduce a novel method for predicting idle channels for secondary users. In this work, we consider the practical issues encountered by a CR user in a wireless environment, such as discontinuous target frequency bands and limited spectrum sensing ability. With the aid of statistical data and traffic prediction techniques, we estimate the probability of a primary user channel appearing vacant. The performance metric used was packet loss ratio (PLR). Figure 1 provides evidence that traffic prediction could yield significant performance gains for CR users in a DSA environment.

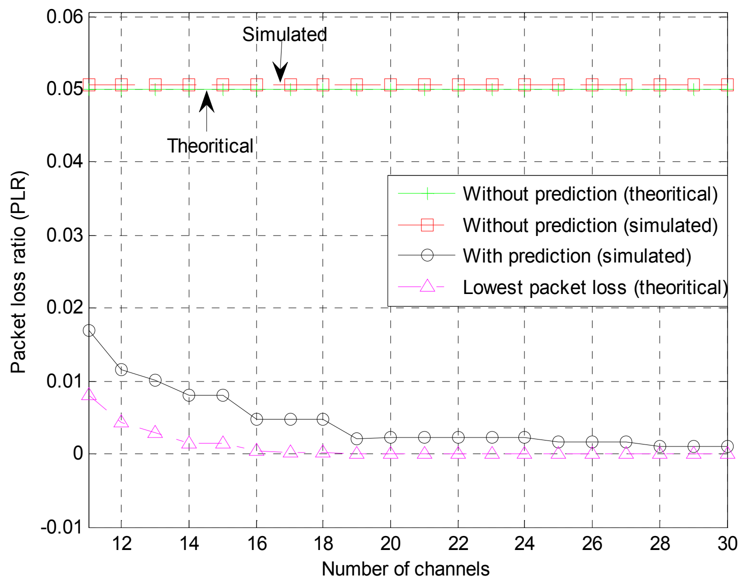

Figure 1: Comparison of PLRs for a CR with and without the use of traffic prediction

3. Cyclostationary signatures.

There are two principal methods used for the detection and classification of unknown signals, namely feature-based, which exploits signal features, such as wavelets and constellations, or likelihood-based, which use hypothesis testing. Second-order cyclostationarity is a low complexity, feature-based method which is inherent in an OFDM signal due to the signal's cyclic prefix (CP), also known as guard interval (GI). These cyclic features of an OFDM signal can be used for the identification and coordination of different signals, modulation formats, systems, networks, as well as for frequency rendezvous [4] [5]. In general, "A signal is said to exhibit cyclostationarity if its cyclic autocorrelation function is nonzero for a nonzero cycle frequency". [6]

Hence, cyclostationary signatures can be used to distinguish between high priority primary users and opportunistic secondary users. They also alleviate the need for a dedicated control channel making them suitable for the self-coordination of CR networks. Making use of such signatures in the development of MAC protocols for CR networks is currently under investigation. [5]

Cyclostationary signatures can be explored using the cyclic autocorrelation function (CAF) in the time-domain (TD) or the spectral correlation function (SCF) in the frequency-domain (FD). Changing the GI length results in peaks appearing at distinct lag indices forming unique patterns, known as cyclic domain profiles (CDPs). [4] The amplitude of these peaks depends on the statistical nature of the signals, which in turn depends on the modulation format, the bit rate and the carrier frequency under consideration. [6] Figure 2 gives an example of a SCF and a CDP (two different scenarios) created artificially by configuring peaks at pre-selected cycle frequencies.

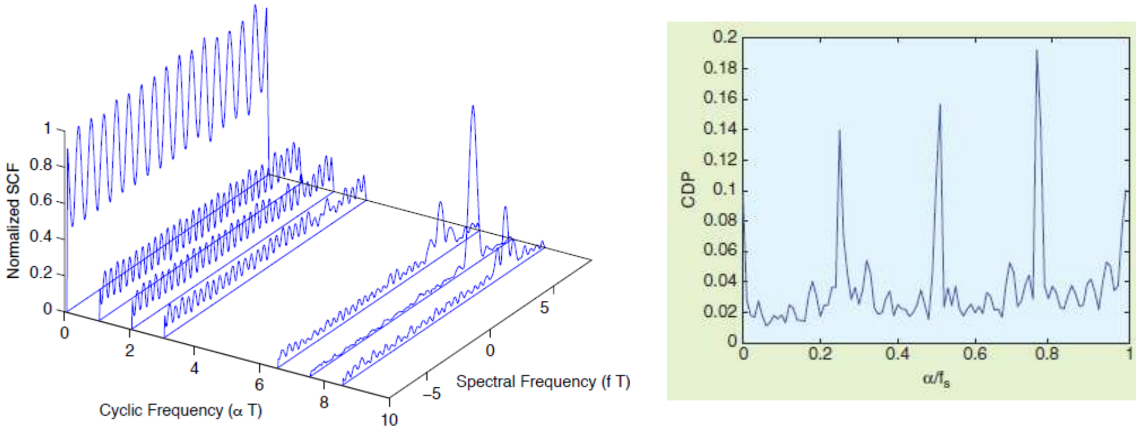

Figure 2: (Left) SCF with embedded cyclostationary signature [5], (Right) CDP example for BPSK [4]

Despite the extensive research in this domain, solid methods for creating these signatures have yet to be developed. In [6], two methods are proposed for artificially embedding a cyclostationary signature in an OFDM signal. The first method involves inserting a specific preamble at the beginning of each frame for a single system giving rise to a unique CAF for that system. This is achieved by choosing a specific subset of subcarriers to be used solely for the preamble. For the second method, a set of subcarriers is dedicated for the total duration of a frame and is common for all symbols in that frame.

Another use of cyclostationarity is for spatial diversity in OFDM-based systems, a technique known as cyclic delay diversity (CDD). The main purpose of CDD is to artificially increase the frequency and time selectivity at the receiver in order to improve the signal-to-noise ratio (SNR). CDD is a special case of delay diversity (DD) the difference being that signals differ in antenna-specific cyclic shifts. This is to avoid inter-symbol interference (ISI) which arises with DD. CDD requires the use of multiple antennas at the transmitter with all signal components combined by linear superposition at the receiver using maximal ratio combining (MRC). The overall transmission power stays the same since the transmitted power per antenna decreases as we increase the number of antennas. [7]

From the above, it seems that CDD is identical to space-time coding (STC). Although the concept is very similar, STC exploits channel coding in conjunction with antenna diversity unlike CDD which exploits only the latter. Furthermore, CDD can be supported by existing transmitter architectures unlike STC which requires non-conformable modifications to be made to standardised systems. [7]

4. Multiple access.

The foremost important performance metric for a multiple access (MA) system is the bit-error-rate (BER). [8] The BER is highly sensitive to interference irrespective of whether this is CCI or MAI. For this reason, a new MA system has recently been proposed [9] called autocorrelation division MA (ADMA), which claims to have the ability to completely eliminate CCI and MAI. Results indicate that ADMA can provide a BER which is up to 10^4 times better compared to code division multiple access (CDMA). The key element of the ADMA system is the ADMA filter. Simulation results [9] show that this filter is capable of recovering a signal even when the interference is 10^3 times stronger than the desired signal. Moreover, the ADMA system can achieve the aforementioned performance gains without the stringent power control and synchronisation required for CDMA. The same work also illustrates that the SINR performance for the ADMA system approaches that for a MMSE receiver.

This new MA system relies on a similar concept as for CDMA in that signals are modified in such a way that they do not interfere with each other. Whereas in CDMA this is achieved via the use of spreading codes which are (nearly) orthogonal between them, in ADMA, signals have to be carefully filtered so their autocorrelation sequences are linearly independent between them. This is the purpose of the ADMA filter, which acts as an interference-blocking filter. If these sequences, known as ADMA codes, are linearly independent between them, then the ADMA system will be more robust than any existing MA system against channel impairments. [9]

Even though the ADMA concept seems promising as a MA scheme in future mobile networks, there are still many issues that need to be resolved to enable its practical implementation. For example, in what way is the ADMA filter obtained? How are the autocorrelation sequences assigned to users? How do we ensure these sequences are linearly independent between them which is the critical condition for interference elimination? These questions and many more need to be answered if ADMA is to compete with existing systems, like CDMA, or alternative MA schemes, like Interleaved DMA (IDMA) in order to be successfully employed in future systems.

To conclude, we consider that future research work should focus on modelling and improving system capacity for next generation mobile networks. Although most of the third generation (3G) wireless technology standards are based on CDMA, this MA method is strongly sensitive to interference, requiring fast and accurate power control [8], thus may prove to be incapable of supporting future user demands. Hence, in view of the discussion presented in the previous sections, bringing together the concepts of cyclostationary signatures and ADMA could yield fruitful outcomes. Finally, it is worth mentioning that while physical layer issues, such as modulation, synchronisation and coding are important, network control, coverage and capacity are even more crucial to deliver the desired data rates and quality of service (QoS) guarantees taking into account the ever-increasing traffic loads.

5. Conclusions.

In this paper, we gave an overview of some hot research topics currently under investigation. Having identified two principal research areas in wireless networks, being that of spectrum availability and system capacity, we then explored the two key technologies that deal with these issues, being cognitive radio and multiple access schemes, respectively. The remainder of the paper defined and explained the concept of cyclostationary signatures which are considered to be the next step in the development of the aforementioned technologies aimed at improving signal detection, network recognition and coordination, as well as capacity enhancement. Future work will address these issues by merging the concepts of cyclostationary signatures with the recently proposed ADMA system.

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