THE DESIGN OF AN LTE-A SYSTEM ENHANCED WITH COGNITIVE RADIO

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ABSTRACT

This paper presents our design of a long-term evolution advanced (LTE-A) system enhanced with cognitive radio (CR) technology. Introductions are given on the key components and functionalities such as spectrum awareness, cognitive engine, location awareness, digital front-end and baseband spectrum shaping. Besides, a research platform implementing the CR-enhanced LTE-A system is presented. According to the goals of our ongoing projects *kogLTE* and *ABSOLUTE*, specific considerations on TV white space (TVWS) and disaster relief scenario are addressed in the system design.

***Index Terms*—** LTE, cognitive radio, software defined radio, spectrum awareness

1. INTRODUCTION

During the past twenty years, the spectral efficiency of cellular system has been increased dramatically from 2G era's about 1 bps/Hz to todays 4G LTE advanced (LTE-A) system's over 20 bps/Hz. Such enormous spectral efficiency requires sophisticated and power-consuming signal processing which nowadays seems to be close to a practical limit when considering relevant feasibility constraints, like the number of multiple antennas in mobile terminals and the inherent noise of radio frequency front-ends. On the other hand, the booming popularity of smartphones and tablets results in a continuous growth of cellular data traffic which further widens the gap between data rates supply and demand. The only technical solution for closing the gap is to increase the available cellular bandwidth either by opening up new spectrum or by refarming the legacy underutilized spectrum. Cognitive radio (CR) can enable wireless system to exploit underutilized spectrum while minimizing or even avoiding causing harmful interference to users with higher priority, which is a promising candidate technology for further enhancing the throughput and reliability of LTE network.

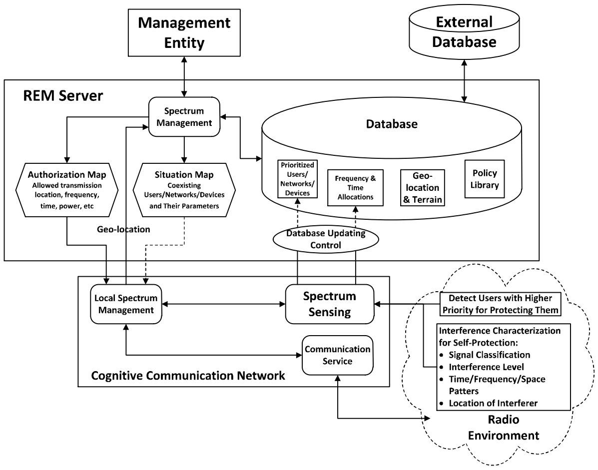

Fig. 1. The Spectrum Awareness Framework

In this paper, the initial design of a CR enhanced LTE-A research platform for the *kogLTE* [1] and *ABSOLUTE* [2] projects is presented. The key components and functionalities such as spectrum awareness, cognitive engine, location awareness, digital front-end and spectral shaping are introduced in respective sections. Besides, this paper also propose a robust spectrum sensing algorithm which is insensitive to noise uncertainty and clock mismatch. Specific considerations on TV white space (TVWS) and disaster relief scenario are addressed in the system design according to the goals of the projects.

2. SPECTRUM AWARENESS FRAMEWORK

Spectrum awareness is the fundamental functionality for enhancing the LTE system with CR, which provides it with the knowledge input of the spectrum environment. In our system design, we address both the spectrum sensing approach and the geo-location database (GDB) approach, which are depicted in the framework illustrated in Fig. 1.

The GDB is based on refining and reasoning of the information from radio environment map (REM), spectrum policies and parameters of user networks/devices, etc. The

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existing GDB approaches mainly aim at authorizing TV whitespace (TVWS) devices to operate with specified parameter (e.g. carrier frequency, transmit power) for protecting incumbent primary user [3]. In addition to this kind of authorization map, more comprehensive situation map with information on coexisting networks/devices' parameters should be provided by GDB and combined with spectrum sensing results for optimizing the coexistence of heterogeneous networks(e.g. cellular systems, TETRA, white space devices and satellite link, etc.) operating in highly dynamic and uncertain disaster relief scenarios.

Spectrum sensing is also important in our design thanks to its versatility and timeliness. We focus on context awareness and interference characterization in designing the sensing mechanism which is far beyond the scope of only detecting the presence of primary user's signal in white space communication. For example, the sensing module can classify the types and extract some parameters of coexisting transmitters, measure the interference pattern in both time and frequency domain and even locate the interferer.

We have studied the improvement of the robustness of spectrum sensing on practical receivers in terms of eliminating spurs and mitigating noise uncertainty problem using the proposed dimension cancelation (DIC) method [4]. In the integration of the sensing techniques into LTE-A system, an important issue is how to achieve in-band sensing in the frequency band occupied by LTE network which doesn't have the inherent quiet period mechanism as in some CR standards such as ECMA-392 and IEEE 802.22. We are considering utilizing the measurement gap of UE and using advanced signal processing techniques suppressing the self-interference as candidate solutions for in-band sensing.

3. ROBUST SIGNAL DETECTION FOR DVB-T

An important precondition for the CR enhanced LTE-A system to operate in TVWS is that legacy TV broadcast should be well protected, which requires the popular DVB-T transmission to be detected at very low SNR level. In [5], it was analyzed that among the signal detection methods, the matched filter based detection has the lowest sample complexity of $O(1/SNR)$, thus it requires the least amount of samples for achieving the same goal of probability of misdetection (PMD) and probability of false alarm (PFA). Working into this direction, we propose a robust sensing method for DVB-T based on the matched filtering of its periodical pilot structure.

Assume $p(t)$ is the pilot signal composed of both continual and scatter pilots with the length of four OFDM symbol lengths $4T_s$. The impulse response of the filter matched to $p(t)$ becomes $q(t) = p^*(4T_s - t)$. In order to reduce the vulnerability to carrier frequency offset, $p(t)$ is split into M segments

$$q_m(t) = q(t + \frac{4T_s}{M}m) \quad m = 0, ..., M-1 \; and \; 0 < t < \frac{4T_s}{M} \quad (1)$$

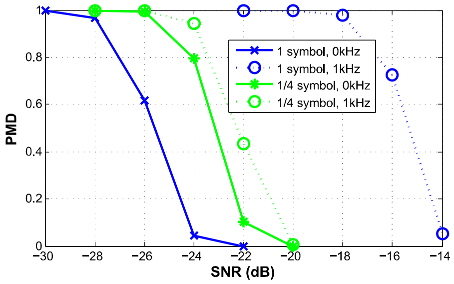

Fig. 2. PMD performance for DVB-T signal(8K DFT, 1/4 CP) with CFO using different segmentation lengths, observation time: 20 ms, PFA: 0.01

which are used to filter the received signal y(t) respectively:

$$y_m(t) = \int_{-\infty}^{+\infty} y(\tau) q_m^*(t - \tau) d\tau. \quad (2)$$

Then the filtered signals $y_m(t)$ are combined together using time shift of $\frac{4T_s}{M}$ in order to strengthen the feature peaks generated by the crosscorrelations: $c(t) = \sum_{m=0}^{M-1} |y_m(t + \frac{4T_s}{M}m)|^2$. The feature peaks can be further strengthened utilizing the pilot structure's period of $4T_s$:

$$d(t) = \sum_n c(t + 4nT_s) \quad 0 < t < 4T_s. \quad (3)$$

Then the detection metric is composed as

$$\Lambda = \frac{\max d(t)}{\int_{-\infty}^{+\infty} |y(\tau)|^2 d\tau} \quad 0 < t < 4T_s, \quad (4)$$

in which the denominator $\int_{-\infty}^{+\infty} |y(\tau)|^2 d\tau$ is used for DIC [4] which can solve the noise uncertainty problem completely.

Some initial simulation results are given in Fig. 2, which shows the PMD performances of the proposed algorithm when carrier frequency offset (CFO) is presented. Assuming the carrier frequency is 594 MHz, the 1 kHz CFO characterizes an oscillator error of about 1.7 ppm. The results show that with smaller segmentation length of $1/4$ OFDM symbol length, thus larger M in (1), the detection performance becomes much more robust against the CFO. Fig. 2 also shows that the stringent requirement of reliable detection below -20 dB SNR can be met with observation time of 20 ms and PFA of 0.01.

4. COGNITIVE ENGINE

The cognitive engine is the brain of the cognitive radio which makes adaptive decisions based on the environmental conditions and capabilities of the radio. Due to this intelligent behaviour, methods from the field of artificial intelligence become very appealing for making rational decisions and optimizing the radio transmission parameters based on the observations of the environment. As an example in [6], genetic algorithm based cognitive engine has been investigated regarding its application to a software-defined radio (SDR) platform.

Besides the application of cognitive engine to reconfigure SDR platform, the scenario called *Dynamic Spectrum Access* (DSA) has received huge attention which aims to cope with the spectrum scarcity issue spotlighted by FCC [6]. In a DSA scenario, unlicensed users are allowed to use the underutilized licensed radio spectrum in a near-realtime manner provided that the licensed users are not subject to harmful interference caused by the unlicensed users. Consequently, an unlicensed user must be able to adjust its transmission parameters dynamically in order not to degrade the performance of licensed users and to make efficient use of the white space spectrum which is the portion of the underutilized licensed spectrum in time, frequency and space.

A classical approach to enhance a traditional communication system with DSA capabilities is using optimization methods. As the task of the cognitive engine in DSA is to maximize its own capacity while keeping the interference under certain level, it is mathematically convenient to formulate this problem as an constrained optimization problem. Further, due to complexity issues the optimization problems can be reformulated as a dual problem by applying the lagrangian duality decomposition method. Hereby is the duality gap an important measure which specifies how close the solution of the dual problem is to the optimal solution of the primal problem. As an example in [7], the authors formulate the subchannel and power allocation problem in a multi-cell OFDMA CR networks as an optimization problem and solve it with the lagrangian decomposition method while maintaining fairness among the secondary devices and keeping the interference to the primary receivers below an estimated threshold.

As already stated above, the methods from the field of artificial intelligence have also been investigated for a cognitive engine. Especially, "*Reinforcement Learning*" algorithms have drawn the most attention. In reinforcement learning the environment is modeled as a Markov decision process where an agent makes a decision based on the predicted state values of the Markovian model, interacts with the environment, observes the changes in the environment and updates the state values. This process is continued until convergence is reached. Due to the Markovian nature of this method, the state transition probabilities have to determined which can be unknown depending on the environment. However, this issue can be solved with the reinforcement learning algorithm called „*Q-Learning*" developed by Watkins in his dissertation [8]. Interestingly, the application of Q-Learning has been done before the concept of cognitive radio was coined by Mitola. In [9] the Q-Learning algorithm has been applied for a dynamic channel assignment procedure for multiple cells where the channel selection is performed based on the time-varying traffic conditions. In the context of DSA for cognitive radios [10] has applied the Q-Learning algorithm to control the aggregated interference at the primary receiver.

5. LOCATION AWARENESS

The motivation behind embodying location awareness in CR has two folds: (1) CR is a promising technical platform to realize location awareness and fix the deficiencies of legacy localization systems, such as flexibility, adaptability, and high quality-of-service (QoS); (2) embodying location awareness in CR brings a number of benefits, e.g. efficient spectrum utilization and improved capacity, and it also enables a variety of location-based applications, such as location-based services, network optimization, transceiver algorithm optimization, and environment characterization [11]. Furthermore, signal-intrinsic capability for accurate localization is a goal of LTE-A as well as fourth generation (4G) networks [12].

According to [11, 13], the architectural framework of a location awareness engine for CR is illustrated in Fig. 3. Goal-driven and autonomous operation, which are two main features distinguishing CR from legacy radios, are managed by the cognitive engine. The cognitive engine maps the final goals to the local goals, and assigns the location-related local goals to the location awareness engine. Just like human being as well as other awareness engines, the mechanisms in location awareness engine to autonomously achieve its local goals mainly consist of sensing, awareness, and adaptation processes. Finally, the cognitive engine collects and combines the results of the assigned local goals to achieve the final goals. The location awareness engine can be utilized by both CR base stations and mobile stations and its detail information is elaborated in [11, 13]. One step towards realization of location awareness for CR is introduced in [14], where a cognitive positioning system (CPS) provides the positioning accuracy specified by the cognitive engine. The CPS is composed of two parts: (1) bandwidth determination, and (2) hybrid overlay and underlay enhanced dynamic spectrum management (H-EDSM) system. The bandwidth determination part calculates the appropriate bandwidth required for the desired positioning accuracy. Then, the H-EDSM system provides optimum available spectrum resources with required bandwidth to the CPS for positioning. Additionally, time-delay estimation in dispersed spectrum CR systems is studied in [15] and range estimation in multicarrier systems in the presence of interference is discussed in [16].

As illustrated in Fig. 3, different engines embodied in CRs are not independent and there are direct or indirect (through cognitive engine) collaborations among engines. The CPS is a good example showing that spectrum awareness engine (with H-EDSM) can assist location awareness engine to achieve its local goals. On the other hand, the retrieved location information can also facilitate spectrum awareness engine to achieve reliable and efficient dynamic spectrum management through geolocation database or local beacon techniques [11]. Simi-

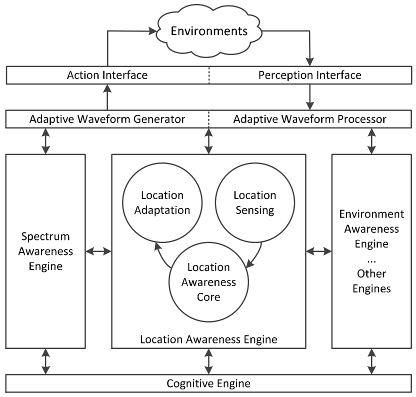

Fig. 3. Architectural framework of a location awareness engine for CRs.

larly, environment awareness engine provides wireless propagation channel information, such as non-line-of-sight (NLOS) [17], to improve localization accuracy and location information can help environment awareness engine to select the optimum empirical model to estimate both large-scale and small-scale statistics since most of them are environment-dependent parameters (e.g. rural, urban, and indoor) [11].

Since CR facilitates opportunistic use of spectral resources, its dynamic nature poses great challenges to localization, as well as communication. Therefore, reliable, efficient, rapid, and low-complexity adaptive localization techniques as well as related tunable/reconfigurable hardware should to be developed, which is crucial for CR to find its proper niche in the practical world and also an active and cutting-edge research area.

6. DIGITAL FRONT-END

Thanks to the development of signal processing, the existing SDR enables the reconfigurability in both baseband and RF front-end; whereas only SDR specified in RF front-end will be discussed here. In order to improve the flexibility, more and more functions implemented in analog domain are shifted into digital domain resulting in digital front-end (DFE). This concept was initially proposed in [18], where the author defined its tasks of channelization and sampling rate conversion (SRC). As illustrated in Fig. 4, the channelization consists of digital down conversion (DDC) and channel filtering in the receiver, corresponding to digital up conversion (DUC) and channel shaping in the transmitter. The main function of SRC, with the category of integer SRC (ISRC) and fractional SRC (FSRC), is to adapt the sampling rate of ADC to the parameter specified by the communication standards. ISRC is applied near ADC or DAC, to keep the sampling rate inside DFE much lower, which can save the processing power. The functions of DFE are in many folds, such as digital predistortion at the transmitter, spectrum sensing in CR capable node, and multi-channel channelization facilitating the multi-channel simultaneous transmission or reception with a single wideband RF front-end.

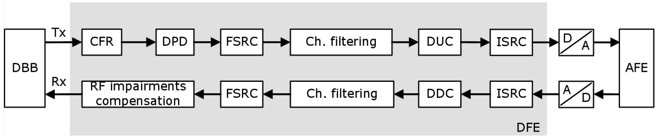

Fig. 4. An example of DFE structure

In LTE-A (Release 10), carrier aggregation (CA) is one of the key enhancements, where three types of CA, i.e., intra-band contiguous, intra-band non-contiguous and inter-band non-contiguous, have been specified. Based on the large-size fast Fourier transform (FFT), multi-channel channelization functionality in DFE can realize at least the first two types of CA. In summary, the DFE can provide a simplified SDR architecture to LTE-A and beyond, especially in the scenario of TVWS where the available spectrum are more fragmented.

7. SPECTRAL SHAPING

The secondary users are allowed to access the white space under the constraint that their spectral power leakage must be strictly suppressed to avoid harmful adjacent-channel interference. Multi-carrier techniques can provide great flexibility in utilizing fragmented spectrum resources for signal transmission. As a candidate transmission scheme for CR, OFDM with rectangular pulse shape as well as filter bank based multi-carrier (FBMC) using various prototype filters have been intensively studied [19, 20].

Since rectangularly pulsed OFDM signals exhibit sidelobes with high power level, effective sidelobe suppression must be applied to OFDM signals. As an example, time windowing scheme applies appropriate windows, such as Hanning window, to the transmitted signal. By letting the signal's amplitude go smoothly to zero at the symbol boundaries, the spectral sidelobes are significantly reduced. Another data-independent approach, referred to as spectral precoding, can also achieve very high sidelobe suppression by making the signal continuous in the border of adjacent OFDM symbols.

To observe the suppression performance, the power spectral density (PSD) of windowing scheme with 64 samples roll-off Hanning (Han 64) and spectral precoding with 6 derivatives (SP n=6), is depicted in Fig. 5, together with the F-BMC scheme with a prototype length of K=4. The spectral mask defined according to the LTE standard is also illustrated. It can be seen that the spectral mask can be conveniently fulfilled by all three schemes. It clearly shows that FMBC outperforms the other two schemes not only by its much better sidelobe suppression, but also by providing a much steeper slope at the edges of the signal band.

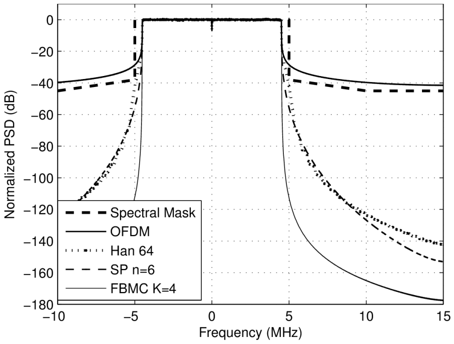

Fig. 5. The PSD of different spectral shaping schemes (more detailed numerical results are in [20]).

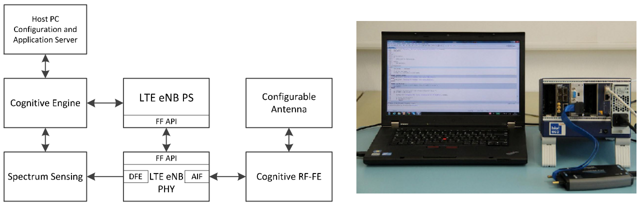

Fig. 6. Cognitive LTE testbed

8. THE COGNITIVE LTE TESTBED

A testbed is under development by DSV and its partners for evaluation and demonstration of a CR-enhanced LTE-A system. The testbed is based on a SDR platform commercially available for small cells base stations and is well suited for applications which require high bandwidth real-time processing. It has been designed for development of next generation radio interfaces like LTE-A and beyond. The functional block diagram of the testbed and the testbed setup are shown in Figure 6. The testbed physical layer (PHY), the spectrum sensing module and the cognitive engine (CE) are implemented on a MicroTCA/AMC module from IAF Braunschweig [21] with two quad-core TI TMS320C6670 DSPs. The testbed protocol stack from Nomor Research, Munich [22] is implemented on an ARM processor platform and communicates with the PHY layer based on the femto forum API (FF API) [23]. The RF front end (RF-FE) of the testbed is connected through CPRI interface, which allows to connect different RF-FE and configurable antennas. Within the kogLTE project, University RWTH Aachen will provide a high dynamic range (HDR) RF-FE for 470 MHz to 900 MHz, and RheinMain University of Applied Science, R uselsheim a highly reconfigurable antenna solution. For the frequency range to be covered in the ABSOLUTE project, the SDR RF-FE by Fraunhofer HHI Berlin will be used, supporting 800 MHz up to 2.7 GHz [24].

9. CONCLUSION

The key components and functionality in designing a CR enhanced LTE-A system are presented with focusing on spectrum awareness, cognitive engine, location awareness, digital front-end and baseband spectrum shaping. The SDR platform based on TI DSP for implementing the system is briefly introduced. As an important capability of protecting incumbent TV broadcast, a practical spectrum sensing algorithm for detecting DVB-T signal at low SNR within short observation time is presented with initial but promising results.

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