EXPANDING LTE NETWORK SPECTRUM WITH COGNITIVE RADIOS - FROM CONCEPT TO IMPLEMENTATION

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ABSTRACT

Wireless data traffic is growing extraordinarily, with new wireless devices such as smart phones and bandwidth-demanding wireless applications such as video streaming becoming ever increasingly popular and widely adopted. Correspondingly, we have also witnessed the phenomenal wireless technology evolutions to support higher system capacities from generation to generation. Long Term Evolution (LTE) has been developed as 4G wireless technology that can support next generation multimedia applications with high capacity and high mobility needs. However, the peak data rate from 3G UMTS to 4G LTE-Advanced only increases 55% annually while global mobile traffic increases 66 times with an annual growth rate of 131% between 2008 and 2013. Clearly there is a huge gap between the growth rate of new air interface and the growth rate of customer's needs. A promising way to alleviate the contention between the actual traffic demands and the actual system capacity growth is to exploit more available spectrum resources. Recently, cognitive radio (CR) technology has been under extensive research and study. It aims to provide abundant new spectrum opportunities by exploiting under-utilized or un-utilized spectrum opportunistically. In this paper, we discuss the technical solutions to expand LTE spectrum with CR technology (LTE-CR), and survey the advances in LTE-CR from both research and implementation aspects. We present detailed key technologies that enable LTE-CR in the TV white space (TVWS) and related standards and regulation progresses. To demonstrate the feasibility of deploying LTE-CR in TVWS, we have conducted extensive system level simulations and also developed a LTE-CR prototype. Both simulation and lab testing results show that applying LTE-CR in TVWS can achieve satisfactory performance.

Index Terms

Cognitive radio, LTE, TV white space, LTE-CR, spectrum sensing, prototype, simulation

1. INTRODUCTION

Wireless traffic volume is expected to expand tremendously in the next few years [1], driven by the new generation of devices (netbooks, smart phones, and other mobile internet devices) and bandwidth hungry applications such as video streaming. Based on the forecast data, global mobile traffic increases 66 times with an annual growth rate of 131% between 2008 and 2013 [2]. The traffic volume generated by consumers is quickly becoming too overwhelming for the existing networks to handle. To address the traffic explosion and capacity demands, there have been three major technologies in the recent trends.

- **Advanced technologies with improved spectral efficiency** - From Release 99 Universal Mobile Telecommunications System (UMTS) to Release 5 High Speed Downlink Packet Access (HSDPA), downlink spectrum efficiency has been improved more than four times. However, when technology evolves from Release 6 High Speed Packet Access (HSPA) with Single-Input-Multiple-Output (SIMO) 1x2 to Release 7 with 64 Quadrature Amplitude Modulation (QAM) and 2x2 Multiple-Input Multiple-Output (MIMO), the system only experiences a modest 10% to 20% improvement in the aggregate system throughput. The trend has shown that wireless networks receive a diminishing spectrum efficiency gain from improvements on the air interface. New technologies other than just improving wireless link level performance such as increasing modulation and coding rates are needed.
- **Higher network density** - Increasing cell density is an effective but expensive approach to adding capacity. Excessive cell sites may also result in excessive interference. Adding sectors, such as from 3 sectors to 6 sectors, is a useful way to approximate the introduction of new cells. But this does not quite double the capacity as the "petals" of 6-sector coverage do not interleave as well as 3-sector coverage, and the fractional overlap of 6-sector is greater.
- **More available frequency spectrums** - The 4G Long Term Evolution (LTE) standard is the preferred development path of HSPA network, and an optional evolutional path for the Code Division Multiple Access (CDMA) networks. It offers a higher data throughput to support new and advanced mobile broadband services. It can also support flexible spectrum operations (from 1.4 MHz to 20 MHz) and adapts to various spectrum scenarios without significantly increasing the control channel overhead.

All three technologies are expected to contribute significantly to the next generation wireless network capacity expansions. In this paper, we focus on the technology that can enable more available spectrum resources. The paramount economic and societal benefits can be derived from a more dynamic and fast-track regulatory approach to unlocking additional spectrum for mobiles. Figure 1 shows the International Mobile Telecom (IMT) spectrum requirements in the next 10 years. As predicted by International Telecommunications Union (ITU), the spectrum demand will be in the order of 1280–1720 MHz by the year 2020 [3]. In a traditional spectrum allocation process, the allocation of additional spectrum will require several years or even more than 10 years. This slow regulation pace will not be able to meet the rapid increasing spectrum demands as shown in Figure 1.

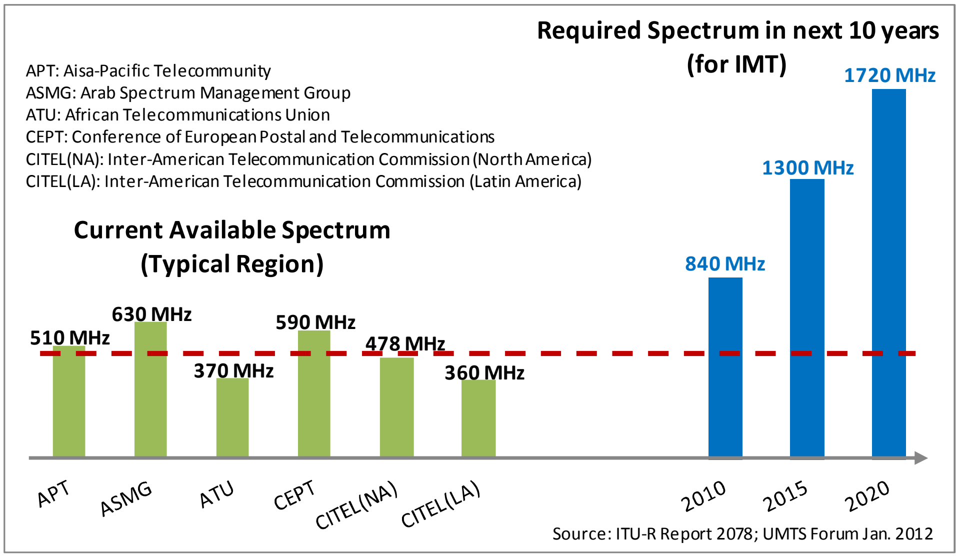


Figure 1: Trend of IMT spectrum requirement

More recently, many researchers are seeking alternatives to unlocking the spectrums. As shown in [4][5][6][7], most of the already allocated spectrums are significantly underutilized or even unused worldwide temporally or geographically. These underutilized or unused spectrums are called white space (WS) in this context. For example, the white spaces in TV UHF band, or simply TVWS, have caused tremendous attentions due to their desirable propagation characteristic. In [6] and [7] the authors evaluated the TVWS availability in USA and UK respectively after the digital switchover has been completed. It has attracted tremendous research interests lately on how to leverage these white space spectrums effectively to help addressing the increasing spectrum requirements.

Cognitive radio (CR) technology has been proposed to effectively resolve the dilemma between the increasing spectrum requirements and scarce spectrum resources. With CR technology, secondary users (SU) cognize the spectrum environment from time to time and choose idle channels for communications. Once the primary user (PU) needs the channel, the SU switches to a different channel to avoid interference to the PU or simply terminates the transmission if there is no idle channel available. The CR technology can provide abundant new spectrum opportunities by exploiting under-utilized spectrum opportunistically. There have been numerous theoretical research efforts and outcomes on CR technology since its inception. In [8] the authors analyzed the system capacity under receiver and spatial spectrum-sharing constraints. The expression of the capacity is obtained when the channel status information is known [8]. In [9] the authors summarized a rich set of research articles featuring advances in theory, design, and analysis of cognitive radio networks. Parallel to the advances of theoretical research in CR, there have been significant industry efforts on prototyping, standardization and commercialization of CR [10][11][12]. In this paper, we analyze the key CR technologies and summarize the related industry research and development progresses. We also present the detailed CR implementation techniques in LTE network, including a prototype model, and system analysis and evaluations.

The rest of this paper is organized as follows. In Section II, we introduce the key technologies in cognitive radios. In Section III, we summarize the standards and regulation progress on CR. In Section IV, we investigate the applications of CR techniques in wireless cellular networks and present the system level simulations and performance analysis, as well as our prototype of a TDD-LTE-CR system. We conclude the paper with Section V.

2. KEY CR ENABLING TECHNOLOGIES

Cognitive radio has emerged as a promising technology to maximize the utilization of the limited radio spectrum while accommodating the increasing amount of services and applications in wireless networks. Key CR technology evolutions and innovations make LTE working in the expanded white space spectrums being more feasible. These key technologies include spectrum sensing, geo-location database and tunable RF technique.

2.1 SPECTRUM SENSING

How to find an available and suitable spectrum for a secondary user is the key to CR technology. During spectrum sensing, a device scans the frequencies to detect the existence of other users. Upon successful detection, the device can operate on the frequencies that are not being used. This method of sensing may not require network connectivity, since the “intelligence” to decide which frequency to use is on the end device rather than on the controlling network. In the following, two major spectrum-sensing algorithms are described [9].

A. Blind detection

A simple alternative for the detection of a primary signal in noise is to employ blind detection. A blind detector without any information about incumbent simply measures the signal received on a primary band during an observation interval. Normally there are two kinds of blind detections, namely, energy detection and covariance matrix detection. Energy detection is a non-coherent detection and is very simple to implement. It assumes that the signal samples are independent and identically distributed and the detection accumulates the signal energy from all samples. Covariance matrix detection determines the different characteristics of noise and signal covariance matrix. This approach is not sensitive to noise uncertainty. The noise covariance matrix is of full rank and only diagonal values are nonzero. Compared to the noise, the signals are always autocorrelated due to the multiple channels and filters at receiver. Therefore, the non-diagonal values in the signal covariance matrix could be non-zero as well.

B. Feature detection

Unlike stationary noise, most communication signals exhibit spectral correlation due to their built-in periodicities such as carrier frequency, bit rate, and cyclic prefixes. Since the spectral correlation properties of different signals are usually unique, feature detection allows a cognitive radio to detect a specific primary signal buried in noise and interference. There are two kinds of feature detections, namely matched filtering detection and cyclostationary detection. For matched filtering detection, if noise is Gaussian distributed and source signal is deterministic and known to the receiver, it is easy to match the source signal and received signal. The test statistics is compared with a threshold to make a decision. For cyclostationary detection, a real communication system usually manipulates a signal by its own means, so that the signal presents special statistical features called cyclostationarity, i.e., their statistical characteristics occur periodically. This detection approach is robust to random noise and interference from other modulated signals, because the noise has only a peak of spectral correlation function at the zero cyclic frequency and the different modulated signals have different unique cyclic frequencies.

2.2 GEO-LOCATION DATABASE

Besides sensing technology, another key CR technology is using a geo-location database [13]. This requires devices to query a database that contains a master list of assigned or available frequencies or pre-defined rights and obligations at a given time in particular locations. Therefore, devices need to be location aware as well as to be able to access to the database. The geo-location database has to understand all the regulatory requirements that determine the coexistence of a primary user with those who are sharing.

In CEPT (The European Conference of Postal and Telecommunications Administrations) database, the geo-location database will calculate the allowable in-band and out-of-band transmission power for devices based on the information of incumbent transmitters and the different locations of WS devices timely. The location calculation is based on a pixel of 100 m by 100 m. And a specific degradation in location probability of incumbent system is used as a criterion to decide the allowable transmission power. The incumbent location probability in each pixel is defined as the probability with which an incumbent receiver would operate correctly at a specific location. When the location of the CR device is changed by more than 100 m, it has to enquire the geo-location database and obtain the new allowable transmission power again. If the device is moving at a high speed, it has to update with the geo-location database frequently. This method provides more accurate transmission power for devices, but it also results in more complex calculations in the geo-location database.

In FCC (Federal Communication Commission) database, the database provides the allowable transmission power of WS devices based on the location of devices and device categories. It is different from the geo-location database in CEPT. Based on the parameters of the devices (e.g., antenna height, fixed or mobile, etc.), it divides the devices into three categories, i.e., fixed devices, Mode I devices and Mode II devices. Each category has a different permissible transmission power. FCC database is simpler than CEPT database since it provides several fixed allowable transmission power levels to the WS devices based only on the device type and location.

Compared with a geo-location database method, sensing method does not need any additional interface protocol. But it is a challenge to detect incumbent signals with a very low power level. On the other hand, the geo-location method is simpler to implement. But it needs to know the location of WS devices and also the interaction between WS devices and geo-location database.

2.3 TUNABLE & RECONFIGURABLE RF TECHNIQUE

A CR system is usually required to be highly flexible and re-configurable. Because a CR system needs to adjust its operation to the environment and to the available radio spectrum, the radio frequency (RF) components of the CR equipment need to operate in a considerably broader bandwidth than the regular base stations and terminals. This certainly places the tough requirements on the new RF components and subsystems. The CR operating band needs to be acquired with quick tuning. The trend has been lately more shifted towards widely tunable narrowband RF front-ends, which improves linearity and channel selection capabilities but on the other hand increases requirements for high performance.

Radio Frequency Micro-Electro-Mechanical Systems (RF-MEMS) [14] is a key enabling technology for reconfigurable radio frequency front end, due to its superior functionality, integration and performance. RF-MEMS have a very good linearity, low power consumption, size reduction, and also have a high integration-level. However, the fabrication and packaging processes of RF-MEMS filters are very complicated. The RF-MEMS filter fabrication process requires depositing thin films of the material on a substrate, which will start with wafers, deposition, lithography, and etching, and end up with having a full fabricated chip.

3. STANDARDS AND REGULATION PROGRESS

Both USA and UK are making great progresses in applying CR techniques to the wireless communication market within TVWS. FCC, the regulator in USA, approved that the television white spaces database system of Spectrum Bridge Inc. can provide service to devices, beginning January 26, 2012. In UK, OFCOM, the independent regulator for the UK communications industries, is pushing the application of CR in TVWS and will release the TVWS spectrum operation permission by the end of 2012. In Europe, CEPT is working on the technical and operational requirements for the operation of CR systems in the 470-790 MHz TVWS. The final version will be published in December 2012. Meanwhile, large scale trials in UK and Finland are already taking place [15].

There are several organizations working on the standardization of CR technologies. IEEE standards series (e.g., IEEE 802.11af, 802.16h, 802.19, etc.) are making the CR technique standardization over TVWS. IEEE 802.11af is an amendment to the IEEE 802.11 baseline standard and intends to operate in the TV white spaces. IEEE 802.16h is designed to enable coexistence among license-exempt systems based on IEEE 802.16 and to facilitate the coexistence of such systems with primary users. IEEE 802.19 is focused on developing coexistence scenarios and possible coexistence metrics to enable the family of IEEE 802 wireless standards to most effectively use TV white space. In European Telecommunications Standards Institute (ETSI) Radio Reconfigurable System (RRS), there are a number of ongoing CR related Work Items (WIs). Geo-location database, as one of the key cognitive radio techniques, is becoming the major task in the TVWS area. The Internet Engineering Task Force (IETF) has initiated a standardization effort to standardize a Protocol to Access White Space databases (PAWS) at the beginning of 2012. The group will standardize formats for communications between devices and databases. Figure 2 shows the current status of CR standardization (including IEEE, ETSI and IETF) processes.

4. APPLYING CR TECHNOLOGY IN LTE NETWORKS

4.1 THE APPLICATION OF CR TECHNOLOGY IN LTE NETWORKS

There are many potential application scenarios for cognitive radio technology, as shown in Figure 3. It can help looking for available spectrums to provide broadband internet access in hot spots, rural and underserved areas. Available spectrum may also be used to provide internet backhaul. With CR technology, large wireless operators can use the white space as a supplement of their licensed spectrum to gain extra capacity.

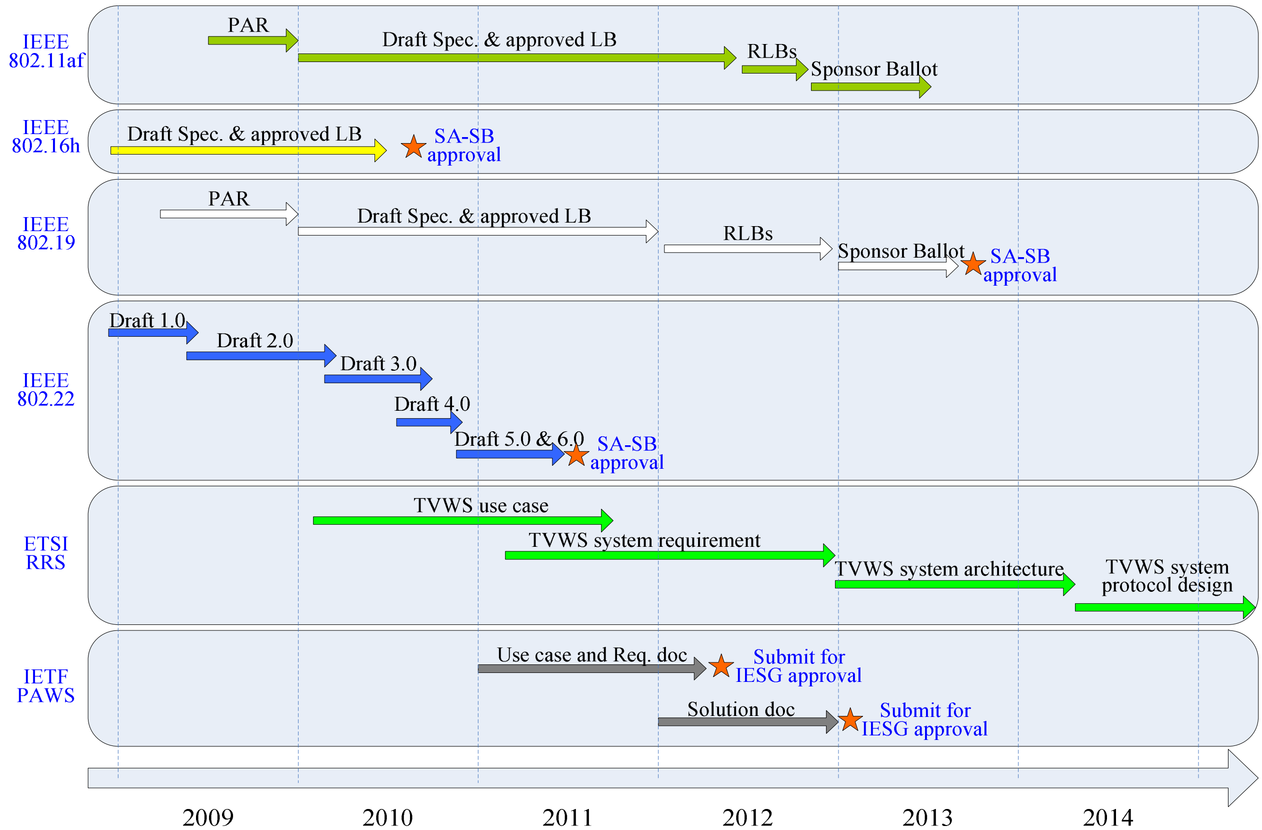


Figure 2: CR standardization status

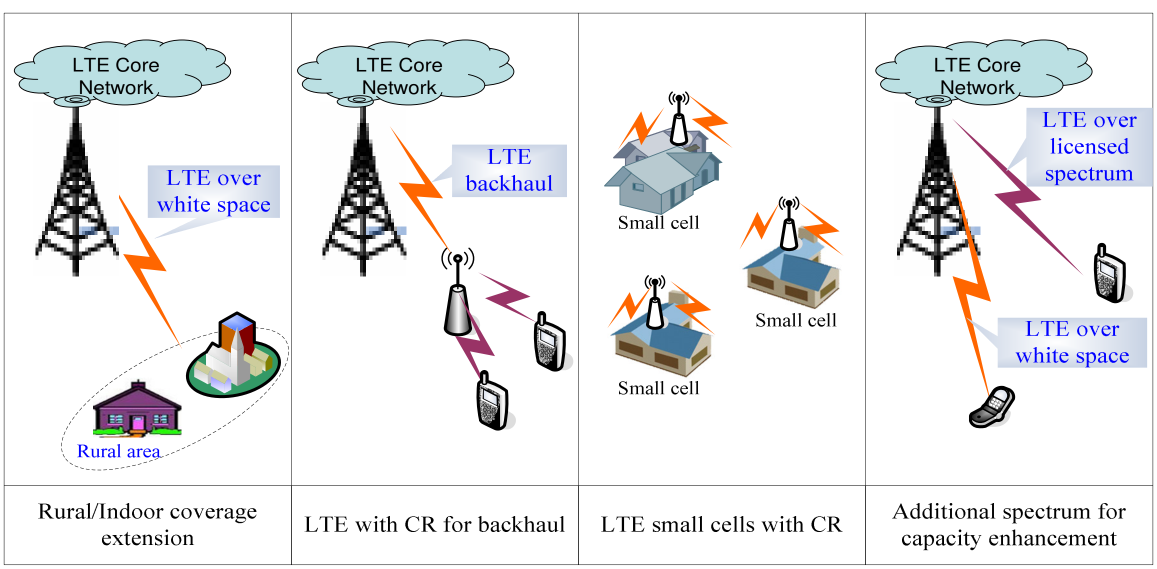


Figure 3: Application scenarios of CR in LTE networks

A. Rural/Indoor coverage extension

In this application scenario broadband internet access is provided by a wide-area network (WAN). A typical deployment is in rural coverage. The broadband internet access is provided to local businesses and residents from a master (i.e. BS) connected to the internet. This deployment scenario is typically characterized by one or more fixed master(s) or BS(s), cells with relatively large radius (tens kilometers up to 100 km), and many available radio channels. Many of the masters or BSs are assumed to be deployed and operated by a single entity and there is a tight coordination between these masters or BSs. The BS in this scenario uses LTE with CR technology and transmits at or below a transmit power threshold established by the local regulator. Each base station uses WS to provide internet connectivity service to multiple slave/end-user devices, which could be either fixed or portable.

B. LTE with CR for backhaul

LTE with CR on WS for relay backhaul requires that both central control point, for example eNB and the relay, have CR functionality/capabilities so that they can select a WS spectrum hole for the backhaul link dynamically. This scenario utilizes the WS for out-of-band relay with higher network reliability, performance and efficiency. The role of CR can be seen as similar to the one described in the previous application scenario.

C. Applying CR to small cell

Adding cell sites is an effective way to add capacity. A small cell needs a low transmission power but more spectrums and a higher bandwidth. Adopting CR technique, LTE small cells will be able to use more available WS spectrum, which can avoid the co-channel interference among adjacent small cells or reduce the interference between a small cell and a Macro cell, and also provide a higher network throughput. LTE small cells with CR can be deployed in-door or outdoor.

D. Additional spectrum for capacity enhancement

In this scenario, WS could provide additional carriers for LTE system to support a higher throughput. Operators use their licensed spectrum as the main component carrier; the main component carrier can provide a reliable link to the users. If some users have extra data rate requirements, BS can use CR to find more WS as a supplementation.

4.2 LTE-CR SYSTEM LEVEL SIMULATIONS

In this section, the system level performance of both TV and Time Division Duplex LTE (TDD-LTE) systems are evaluated when CR technology is applied. The simulation follows the 3GPP evaluation methodology. TDD-LTE cells are deployed around TV coverage edge and keep a distance L from the TV tower. TDD-LTE system operates at 766 MHz ~ 806 MHz and operation bandwidth is 5 MHz. 1x2 SIMO is used in TDD-LTE. As the incumbent system, TV system has a transmission power of 1 kWatt. The TV transmitter height is 300 meter. More detailed assumptions can be found in [10].

A. TV system performance

A TDD-LTE transmission will cause strong interference to the nearby TV receivers that operate under the same spectrum and thus shrink the TV coverage radius. The coverage loss is defined as the radio of the number of TV users which are out of the TV coverage radius to the total number of TV users. Figure 4 shows the TV coverage loss as a function of the separation distance between TV cell-edge and TDD-LTE system edge. In the case of LTE without CR, when the separation distance is zero, TV system coverage loss is about 7%-12%. The TV coverage loss results from the interference caused by the TDD-LTE system. In the case of LTE with CR, even with a separation distance at zero, TV coverage loss is still no more than 1.2%. So the TV coverage loss is trivial when the TDD-LTE is enabled with CR.

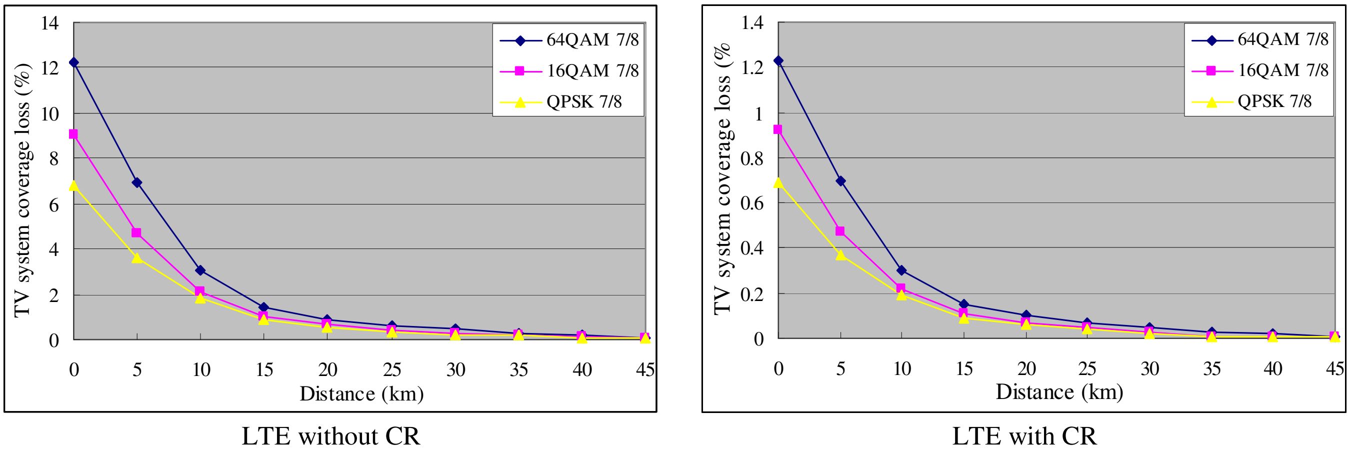
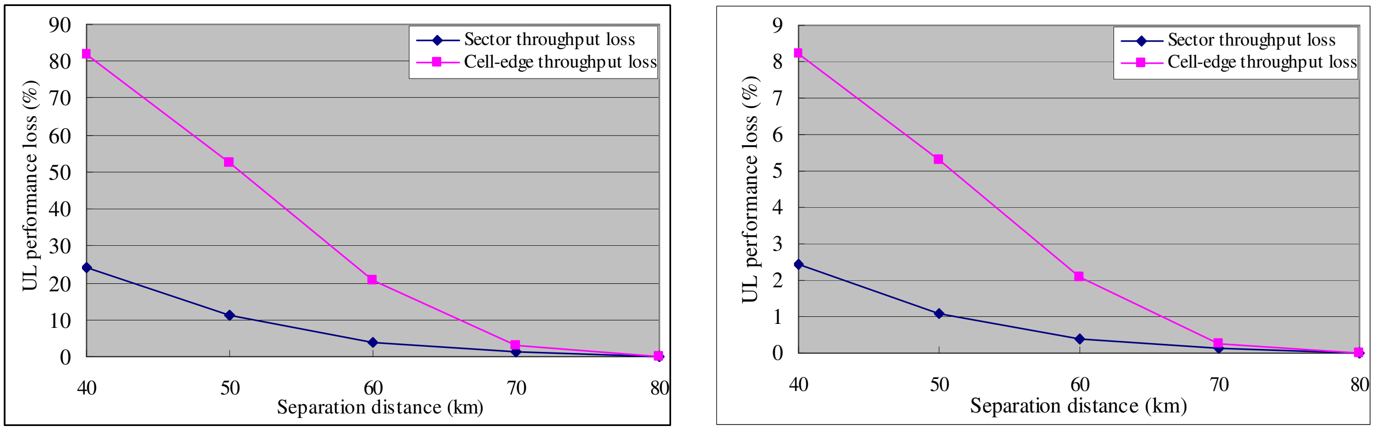


Figure 4: TV coverage loss

B. TDD-LTE system performance

Since the height of eNB receiver is about 35 meters while the height of UE is only 1.5 meters, and eNB receiver has a higher receiving sensitivity than UE, so it is obvious that LTE UL transmission is more easily interfered by TV transmission than its DL transmission. Figure 5 shows the system UL performance loss for a LTE system that is co-deployed with a TV system in the same spectrum with or without CR capability. When the distance is less than 70 km, LTE UL performance loss is more than 5%. When the distance is equal to 40 km, the cell-edge UL performance loss is even higher than 80% while the sector UL performance loss is about 25%. But fortunately, this impact decreases sharply when the separation distance goes up. TV tower can cause detrimental interference to LTE uplink transmission because TV power is much higher than the UE transmission power on the uplink.

When LTE is enabled with CR technology, we find that LTE system performance has a much smaller degradation than that with no CR capability. At the same time, TV system coverage loss is also quite small as shown earlier. CR-enabled LTE system can quickly detect the primary system and switch to other vacant channels in time. The interference between LTE system and TV system is reduced and avoided effectively. With small performance loss, LTE system can increase its capacity greatly by using free TVWS.



LTE without CR LTE with CR

Figure 5: LTE UL performance loss

4.3 PROTOTYPE IMPLEMENTATION AND LAB TEST RESULTS

We have further developed an LTE-CR prototype based on LTE TDD technology to demonstrate the feasibility of dynamically utilizing TVWS spectrum by using CR technique in LTE TDD system. The basic system diagram is shown in Figure 6:

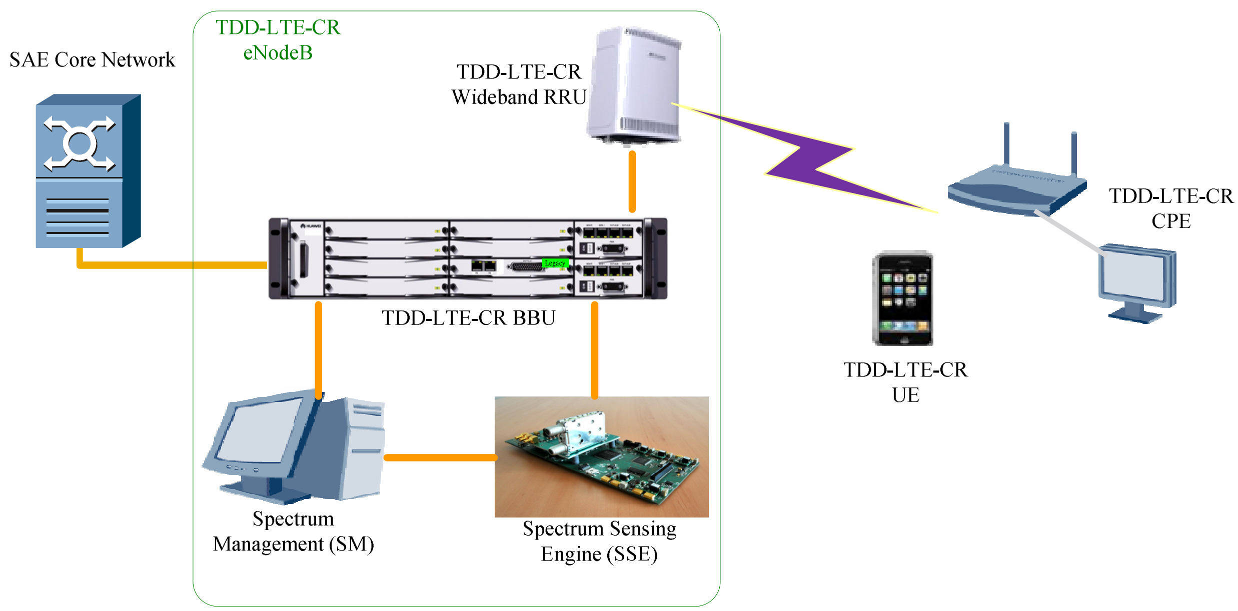


Figure 6: LTE TDD CR prototype system

This prototype system consists of TDD-LTE-CR eNB, TDD-LTE-CR CPE and a traditional System Architecture Evolution (SAE) core network. It is an end-to-end LTE TDD system compatible with 3GPP R9 protocol. The prototype system is capable of detecting the incumbent and performing spectrum switching. The prototype spectrum sensing engine can detect whether the TV spectrum is empty or occupied by the incumbent user, based on which the system determines what spectrum is suitable for a specific eNodeB transmission. When the system is operating over an idle TV channel, it always monitors whether the current TV channel will be needed by the incumbent user or not. If yes, the sensing engine will need to find a new empty TV channel that the LTE-CR system can handover to. If a new channel is decided, the system will execute the spectrum switching procedure simultaneously at both eNodeB and served UEs so that services continuity can be maintained.

The TDD-LTE-CR eNB consists of the following components: a wideband CR Radio Remote Unit (RRU), a Base Band Unit (BBU), a Spectrum Sensing Engine (SSE) and a Spectrum Management (SM). The wideband CR RRU is a newly developed RF unit which can support the frequency range from 470 MHz to 806 MHz. This range covers the entire TV spectrum. The operating bandwidth can be either 5 or 10 MHz. The maximal eNB transmission power is 10 Watt. The dynamic frequency hopping in the RRU is about tens nano-seconds. We use Huawei's commercial TDD-LTE eNodeB BBU hardware in the prototype system. It supports spectrum handover function that can smoothly change the working frequency and system operating bandwidth when the current spectrum is re-occupied by the incumbent TV signals so that the service continuity can be guaranteed. The SSE component supports the TV frequency range of 470 – 806 MHz as well as TV signals sensing. It is designed to meet a sensing sensitivity of -114 dBm, which is required by FCC for fixed outdoor scenario. The sensing can be performed in TDD-LTE Guard Period (GP) and has no impact to the TDD-LTE system nominal operation. The SM has a capability to access the spectrum geo-location database complying with both FCC and OFCOM rules. It can optimize the spectrum usage based on sensing results and available spectrum information from database. TD-LTE-CR Customer Premises Equipment (CPE) also includes a wideband CR RRU with a maximum 500 mW power and a BBU unit that is based on Huawei's LTE TDD testing UE BBU with spectrum handover functions.

Based on the prototype system, we conducted a lab test to validate the sensing capability, spectrum switching function and system performance. According to the test outcomes, the LTE-CR prototype processes a high detection sensitivity of -114 dBm. When the incumbent TV user occurs in the channel occupied by the LTE-CR system, the LTE-CR prototype can quickly finish the spectrum switching within 100 ms without any interference to the incumbent system. Meanwhile, the LTE-CR prototype system demonstrates a similar system level performance, i.e., throughput, SINR distribution, to the LTE system operating in its own licensed band.

5. CONCLUSIONS

The application of CR technology will resolve the dilemma between the increasing spectrum demands and spectrum resource shortage. The industry, standards and regulations are all making progresses on CR over white space, especially TVWS. This paper discusses the major technical solutions to expand LTE spectrum into TVWS with CR technology, and presents the advances in LTE-CR from both research and the implementation aspects. Detailed key technologies that enable LTE-CR in TVWS and related standards and regulation progresses are presented. Extensive system level simulations and lab prototype testing results have validated the feasibility of deploying LTE-CR in TVWS.

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