INTERDIGITAL

WHITE PAPER

Dynamic Spectrum Management

Spectrum harvesting through the allocation and aggregation of contiguous and non-contiguous licensed, unlicensed, and TV white space frequency channels

October 2012

Contents

1 Executive Summary

The rapid adoption of smartphones has overwhelmed wireless networks with traffic, and operators have struggled to provide the bandwidth to meet the demand. Industry experts expect traffic to skyrocket further in the coming years, further widening the bandwidth supply-demand gap. Any new licensed band spectrum is likely to be too little, too late, to meet the challenges given the regulatory and competitive environment; and spectrum re-farming approaches are seen as too expensive and time-consuming.

As a more compelling alternative, spectrum sharing enables wireless systems to harvest underutilized swathes of spectrum, which would vastly increase the efficiency of spectrum usage, as opposed to simply releasing new spectrum. The opening up of TV White Space (TVWS) spectrum by the FCC in the

U.S. and Ofcom in the U.K. are early examples of the potential for spectrum sharing. Additional proposals would further allow the use of a variety of other government bands in the U.S. and U.K. for spectrum sharing (as documented in the recent PCAST proposal to the U.S. President [7]).

As a pioneer and innovator of advanced wireless solutions, InterDigital has developed innovative spectrum sharing technology. InterDigital's Dynamic Spectrum Management (DSM) solutions exploit and aggregate the capacity of underutilized bands to dynamically add more capacity to commercial LTE and Wi-Fi® systems – dramatically supplementing bandwidth. DSM is a holistic approach that combines pioneering technology advances such as radio frequency (RF) sensing, geo-location database-coordinated access, radio resource management and wireless access extensions, to dramatically increase capacity, significantly improve coverage and provide substantial mitigation of interference. As a result, new applications and services are now made possible in real-world deployments including:

- Wi-Fi access augmentation
- Cellular access augmentation (FDD and TDD)
- Machine-to-Machine (M2M) communications
- Backhaul and last-mile access
- Multi-tier spectrum sharing models, including Licensed Shared Access (LSA), inter-operator sharing and approaches such as proposed by the PCAST recommendation.

InterDigital's Wi-Fi (DSM-Wi-Fi) and LTE (DSM-LTE) solutions are being designed for standards-based interoperability to enable scalable and cost-effective solutions. InterDigital is working actively to lead initiatives within key standards such as ETSI, 3GPP and 802.11 to foster adoption of spectrum sharing capabilities. InterDigital is working across the ecosystem to drive market adoption.

2 The Current State of Spectrum Sharing

The popularity of the smartphone and the resulting increase in the volume of wireless data traffic has created a large chasm between bandwidth supply and demand [1][2]. An 18-fold increase in mobile data traffic is predicted over the next 5 years, with video being the dominant traffic profile (70.5%) driving the increase in demand [3][4]. Analysts predict a bandwidth shortage of 275 MHz by 2014 [6]. The wireless industry has called on governments and regulators to open up and re-farm underutilized spectrum. However, new spectrum is scarce, and re-farming underutilized spectrum is expensive and time-consuming. The National Telecom & Information Administration (NTIA) reported recently [5] that the re-farming of the 1755-1850 MHz band would require 10 years and 18 billion dollars!

An attractive and less expensive alternative to re-farming spectrum is to maximize the use of under-utilized bands through spectrum sharing. Governments and regulators across the world are beginning to address the spectrum crunch through spectrum sharing, as evidenced by the recent reports from PCAST: 'Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth'[7], and the European Commission: 'Promoting the shared use of radio spectrum resources in the internal market' [8] which both recommend opening up large amounts of spectrum for sharing. The transition to digital television transmission has resulted in the opening up of new spectrum bands - referred to as TV white space (TVWS) - in both the U.S. and Europe. In the United States, the FCC ruled in 2010 [9] that TVWS spectrum be open for unlicensed use by commercial devices, provided that they do not interfere with licensed (primary) services (including DTV broadcasters and wireless microphone users). Many in the government and industry view this ruling as a pilot and model for sharing spectrum. For example, the FCC recently published a Notice of Proposed Rulemaking (NPRM) on the 4.9 GHZ public safety band [10] in which they are proposing to coordinate use of the spectrum through a geo-location database, as well as allow non-public safety users to share the band. In addition the FCC has indicated that it will act by the end of 2012 on one of the PCAST recommendations [7] to allow sharing of the 3.5 GHz band [12][11] between federal agencies and commercial systems.

Recognizing this trend, the industry and standards bodies have undertaken efforts to standardize the operation of wireless systems in shared spectrum. Many prominent companies - including Microsoft [13] and Google [14] - are actively promoting the use of shared spectrum. Other companies focused on promoting TVWS use and developing products include Spectrum Bridge (first approved TVWS database administrator in the U.S.), Telcordia (database administrator), Shared Spectrum (RF sensing), Neul (M2M products), KTS wireless (first FCC approved radio), Adaptrum (radio), and 6Harmonics (radio).

IEEE 802.11 has already begun a standardization effort to allow operation within this spectrum (802.11af: Wireless LAN in TV White Space [15]), and it is expected that LTE operators will also follow suit in an effort to address their bandwidth issues. For example, the aggregation of licensed and TVWS bands would expand the pool of spectrum for the delivery of wireless services by operators. Furthermore, ETSI RRS [16] defines use cases and deployment scenarios for the operation of Reconfigurable Radio Systems (RRS) within White Spaces in the UHF 470-790 MHz frequency band for Europe and discusses methods for protecting the primary/incumbent users (TV broadcasts and wireless microphones). ETSI RRS will be standardizing systems that operate in TVWS, and is currently working on feasibility studies and system requirements for TVWS operation [17][18]. In the U.K., Ofcom has begun the development of a Voluntary National Specification (VNS) that lays out the rules and requirements for devices using UHF TV Band White Spaces.

3 InterDigital's Solution

DSM represents a holistic and evolutionary approach towards spectrum sharing by enhancing existing radio access technologies (i.e. 802.11 and LTE), and InterDigital has pioneered shared spectrum technologies, in line with the company's vision of a "Network of Networks." InterDigital has also collaborated with leading companies, such as Ittiam Systems, Spectrum Bridge, Shared Spectrum, and Radisys, to develop complete systems that include both a geo-location database and integrated sensing, leveraging sensing for both interference management and primary user detection. The benefits of InterDigital's approach are scalability, cost-effectiveness and interoperability amongst a large number of devices. The DSM system is particularly well-suited for a number of emerging network topographies and use cases, including hot spots, network offload, small cells, campus and enterprise deployments, M2M and others. InterDigital has developed complementary DSM solutions for 802.11 technology (DSM-Wi-Fi) and LTE technology (DSM-LTE), both of which have been designed to operate in shared spectrum.

3.1 InterDigital DSM Wi-Fi System Implementation

DSM Wi-Fi has been designed initially to operate in U.S. TVWS spectrum per FCC rules [19], yet is easily adapted to support operation in the U.K. or in other countries as regulations are finalized.

Key attributes of the InterDigital DSM Wi-Fi platform are:

- A modified commercial-grade 802.11n MAC and PHY solution operating over TV whitespace spectrum developed in co-operation with Ittiam Systems Ltd.
- A wideband digital transceiver capable of spanning TV band spectrum from 512 MHz to 698 MHz, with a high spurious-free dynamic range, that meets or surpasses FCC requirements
- Dynamic spectrum allocation of TVWS channels from channel 21 through channel 51 (excluding channel 37)
- Aggregation of up to 4 non-contiguous 5 MHz TVWS channels
- Internet interface to FCC approved TVWS database from Spectrum Bridge
- Support of Mode I, Mode II and sensing-only devices as stipulated in FCC part 15, subpart H – Television Band Devices [19]
- Sensing solution provided by Shared Spectrum Company that enables sensing of Digital/Analog TV and Microphone signals as per FCC rules [19]
- Fast and robust channel selection and assignment providing effective interference management

The DSM Wi-Fi system is based on the IEEE 802.11n [20] standard and enhanced to support reliable and flexible operation in TVWS bands including non-contiguous channel aggregation [26]. As shown in Figure 1, the system consists of DSM clients and a DSM Engine that is typically embedded in an Access Point or other infrastructure device. The DSM Engine is the central radio resource controller, and uses inputs from sensing measurements and an authorized spectrum database to allocate and aggregate contiguous and non-contiguous channels.

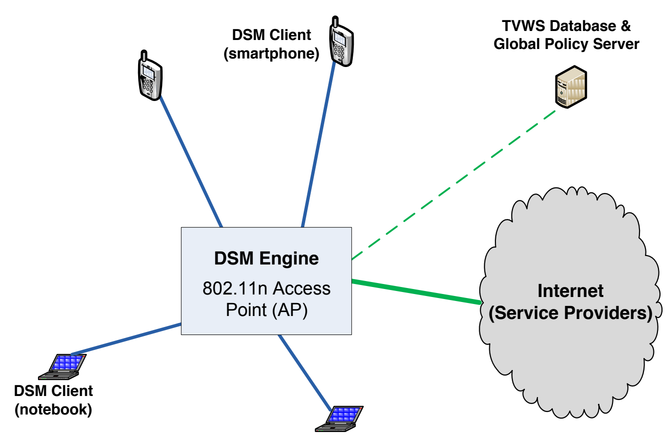

Figure 1: DSM System Architecture

The DSM Wi-Fi system allows aggregating up to four non-contiguous TVWS channels using a wideband radio, multiple IEEE 802.11n PHYs down-scaled for the channel bandwidth, and a modified MAC layer. The aggregation is done in the MAC layer which allows system flexibility by tailoring MAC Protocol Data Units (PDUs) to fit the channel quality and bandwidth of each PHY channel. Furthermore, at transmission time, if one or more channels are busy, only the MAC PDUs associated with the busy channels are deferred, while the other MAC PDUs associated are transmitted. InterDigital's current implementation allows for the MAC layer to aggregate up to four non-contiguous channels.

The DSM Wi-Fi Access Point (AP) and clients are implemented using two identical hardware platforms that are loaded with different software builds. The DSM AP/Client platform, shown in Figure 2, consists of multiple hardware boards housed in an enclosure, featuring:

- An 802.11n WLAN modem board that is configured as either a DSM Wi-Fi access point or a DSM Wi-Fi client
- A Digital Baseband module that contains the interface to the RF modules board and the sensing processor module
- Two wideband radio modules that provide simultaneous access to multiple channels for data transmission and sensing

Each 802.11n PHY module uses a clock speed scaled down by a factor of 4 to operate in a 6 MHz TVWS channel. The platform operates with 115VAC 60 Hz as primary power.

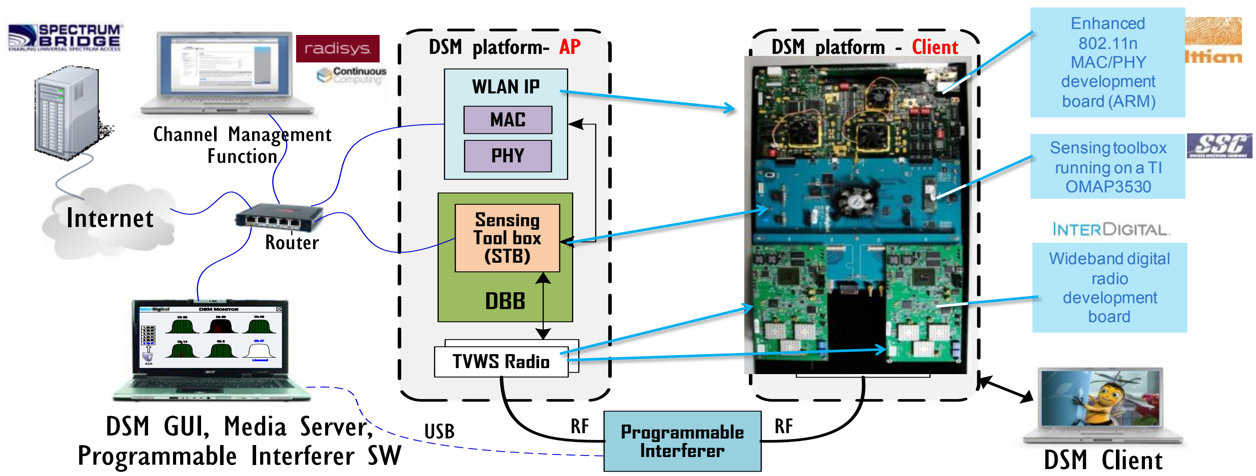

Figure 2: Wi-Fi Demonstration Platform AP/Client

3.2 InterDigital DSM-LTE System Implementation

The DSM-LTE system, based on 3GPP LTE Release 10, has been designed to efficiently operate in both licensed spectrum and the license-exempt TVWS spectrum and to ensure that operation over TVWS channels is as robust and reliable as licensed communication. Key features include:

- Aggregation across licensed and TVWS spectrum
- Sensing to monitor and dynamically switch TVWS channels in response to the detection of primary users and/or interference from secondary users
- An interface to a geo-location database to assess the available TVWS channels
- Co-existence mechanisms to share channels with other secondary systems such as Wi-Fi

The DSM-LTE system has been optimized to operate in small cells to align with current FCC TVWS regulations that impose power limits and antenna height constraints; however, the technology can be extended to large cell deployments. Typical DSM-LTE femto deployments can benefit from using TVWS spectrum to mitigate interference to and from macro umbrella cells. The technology can also aggregate two or more carriers for high data rate applications without the operator needing to add more licensed spectrum.

The prototype DSM-LTE system in the Figure 3 below consists of:

- An LTE protocol stack provided by TATA ELXSI
- A sensing solution from Shared Spectrum
- Interface to the geo-location database from Spectrum Bridge
- A TVWS radio based on a chipset from Lime Microsystems

The system can aggregate up to two 5MHz carriers in TVWS spectrum to a band I or II downlink FDD licensed LTE carrier.

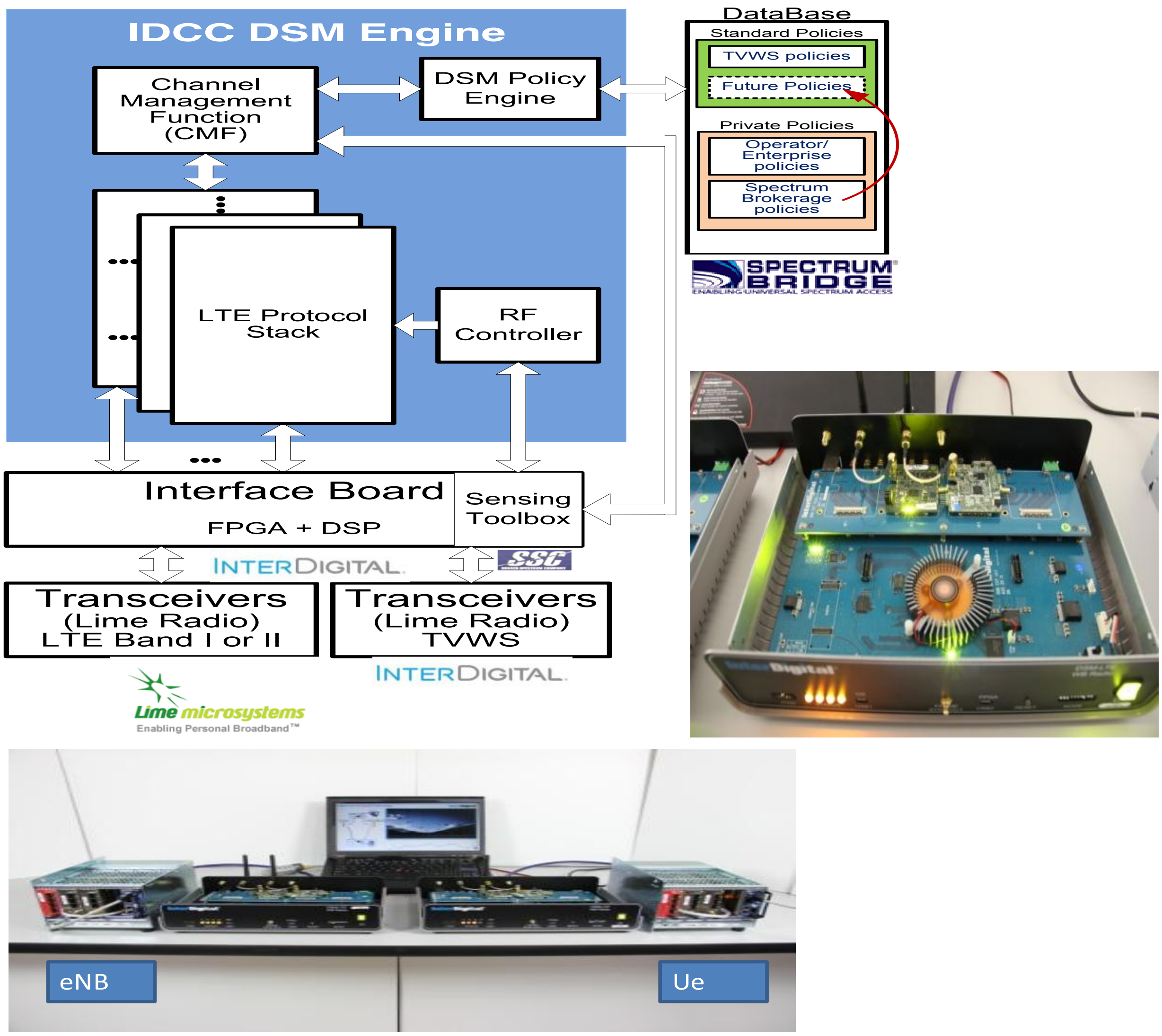

Figure 3: DSM LTE System

4 Key Use Cases for Shared Spectrum

The use of shared spectrum opens up new opportunities for both existing Mobile Network Operators (MNOs), and new entrants. Several interesting use cases, like Wi-Fi/Cellular access augmentation, M2M communications, backhaul and last mile access, and multi-tier spectrum sharing models, can benefit from the use of shared spectrum. The benefits of shared spectrum will depend on the characteristics of the spectrum being shared as well as the regulatory rules associated with the spectrum. The first implementation has been developed to operate within the TVWS regulatory framework; however, the technology is adaptable to any new allocation of shared spectrum.

4.1 Wi-Fi Access Augmentation

A key use case for shared spectrum is Wi-Fi Access augmentation. Wi-Fi currently operates in the unlicensed bands 2.4 and 5.0 GHz. Enabling Wi-Fi operation in shared spectrum can benefit residential, enterprise, hotspot, and metropolitan deployments in many ways:

- Increased capacity: Wi-Fi bands are often congested, particularly in high traffic public areas. Using shared spectrum increases the number of available frequency channels, contributing to user and network capacity.
- Increased reliability and robustness through channel management and aggregation: Unlicensed bands are typically harsh environments with various devices contending for a limited number of channels. The ability to select from more channels, assess channel quality, and choose the best among available alternatives is a clear advantage. Moreover, the ability to aggregate and switch between non-contiguous channels provides another measure of flexibility for finding and utilizing the maximum amount of available spectrum, avoiding interference, and co-existing with other users.
- Longer range operation and improved indoor penetration: Using TVWS bands can increase range by up to 3x compared to operation in the ISM bands, with less attenuation from walls and other building materials, better propagation around obstructions, and greater tolerance of non-line of sight conditions. These features are desirable for metropolitan and indoor-to-outdoor deployments, and are of particular interest to fixed/non-cellular operators, cable providers and new entrants.

4.2 Cellular Access Augmentation

Using shared spectrum as offload or capacity relief is a very interesting use case for established operators that may already be using, or considering the use of, unlicensed bands for Wi-Fi offload. Adapting LTE to operate in shared spectrum can be very beneficial as LTE is already a more efficient and reliable technology than Wi-Fi, and intrinsically supports non-contiguous carrier aggregation. Established operators can leverage existing infrastructure to integrate and aggregate shared spectrum with currently licensed LTE spectrum.

This use case also aligns with the current trend towards deployment of small cells, where LTE in shared spectrum can be the small cell air interface technology. This can alleviate the concern about small cells needing some portion of an operator's licensed spectrum, or small cells operating in the same licensed spectrum as the macro overlay where the resulting interference can reduce the potential network capacity improvements.

4.3 M2M Communications

The use of shared spectrum for M2M communications seems to be a natural fit, given the anticipated explosion of M2M devices. Some devices will require low latency and guaranteed connectivity, but many will be non-real time and compatible with opportunistic access protocols. Using shared spectrum, along with the channel management, can provide the robust and reliable radio connections required by M2M systems without tapping capacity from already congested licensed bands.

4.4 Backhaul and Last Mile access

Providing a flexible and cost-effective backhaul solution is critical to the success of wide scale small cell deployment, and using wired or fixed links may be difficult due to the sheer numbers and installation costs. Shared spectrum is a suitable backhaul technology provided some type of guaranteed access is available. Enhanced spectrum database capabilities that facilitate agreements among spectrum holders and potential users is one approach that can address these needs. Further, new backhaul architectures, mesh networks for example, are a way to combine guaranteed capacity with ways to handle peak situations.

Shared spectrum, particularly TVWS with its excellent long range characteristics, combined with the robustness and reliability afforded by channel aggregation, channel management and interference management is also seen as a solution in last mile access in cases where wired deployment is problematic and costly.

4.5 Multi-Tier Spectrum Sharing Models

The need for guaranteed access in several of the use cases described above is often cited as a concern in relying on shared spectrum. Channel availability may be limited due to congestion, interference, or regulatory constraints, particularly in densely populated areas. Incorporating models that can provide a degree of guaranteed access to the spectrum can augment the intelligent channel management techniques, and ensure a minimum acceptable QoS. The model proposed by PCAST [7] provides for three tiers: Primary users (incumbents such as the federal agencies), Secondary users (provide a degree of guaranteed access for a fee), and Tertiary users (opportunistic users, no guarantees). The intention is to control the use of the spectrum through an intelligent geo-location database that the spectrum users must consult.

5 Key Differentiators

InterDigital's DSM-Wi-Fi and DSM-LTE systems incorporate (4) four key features necessary for efficient operation in shared spectrum such as TVWS:

- Co-existence
- Non-contiguous channel aggregation
- Robust channel management
- Flexible wideband radio

5.1 Co-existence

InterDigital believes that the success of shared spectrum - such as TVWS - depends on both the availability of spectrum and quality of service that can be obtained. Without co-existence mechanisms between users of the spectrum it will be difficult to guarantee reliable service. Coexistence between multiple systems over a shared bandwidth may be achieved through a coordinated mechanism, a non-coordinated mechanism, or some hybrid combination of these.

Coordinated mechanisms rely on a coexistence infrastructure that is aware of how spectrum is being used in a geographical area, and may use this knowledge to manage how spectrum is allocated to specific systems, for example by assigning a specific channel to a system. Both elements (awareness and management) rely on a communication framework between the systems using the spectrum, the coexistence infrastructure performing the coordination task, and, in the case of TVWS, the database maintaining the list of available channels. The awareness comes from the systems providing feedback to the coexistence infrastructure about what they "see" (i.e. sense) and the channels they have selected for use. In addition, the systems may supply value-added information to the coexistence infrastructure which may provide insight into how the system intends to use the spectrum. The management allows the coexistence infrastructure to collect the sensing information (and any value-added information) and guide which channel is allocated to which system. If necessary, it also allows the coexistence infrastructure to direct a system to release a channel, to modify how the system is using a channel (e.g. change maximum transmission power), or even to change the system operating channel (e.g. swap channel x for channel y). The coexistence infrastructure can be implemented via a single centralized entity or be distributed across a number of nodes. Numerous standardization efforts have been undertaken to try to define this coexistence infrastructure. In particular, IEEE 802.19 is defining a distributed solution that collects information about the RF environment, identifies any coexistence problems, and finds solutions to these problems [21]. ETSI RRS will also be defining a coexistence architecture for systems operating in TVWS. IETF PAWS is somewhat complementary as it is defining the protocol for communication between the coexistence entities [22].

Since it will not be possible to guarantee that all systems will rely on the same coordinated mechanism, it is likely that two nearby systems will try to operate in the same channel within the same band. To address these situations, a number of non-coordinated mechanisms exist for coexistence. CSMA is commonly used as a non-coordinated mechanism for coexisting networks. The coexistence of Wi-Fi with ZigBee® and Bluetooth® is managed by carrier sensing [23], [24]. A well known example of a CSMA mechanism is the distributed coordination function (DCF) of the 802.11 MAC, described in [20]. The DCF uses the carrier sense multiple access with a collision avoidance (CSMA/CA) mechanism for contention-based access. In CSMA/CA, a device (AP or Client) with a new packet ready for transmission senses the channel to determine the channel availability. If the channel is detected idle for a DIFS interval, the device starts the packet transmission. Otherwise, the device continues to monitor whether the channel is busy or idle using an exponential back-off mechanism, which helps reduce packet collisions.

To enable co-existence between LTE and Wi-Fi systems operating in shared spectrum, InterDigital has developed both coordinated (i.e. database) and non-coordinated approaches. One such non-coordinated approach consists of introducing "coexistence gaps" into the LTE transmission. During the gaps, the LTE system is silent and does not transmit any data, control, or reference symbols. At the end of the coexistence gap, the LTE system simply resumes transmission, without attempting to assess the channel availability. The introduction of coexistence gaps provides the Wi-Fi system with an opportunity to access the channel, and is a simple and effective solution as it takes advantage of the CSMA nature of the Wi-Fi system. Simulation results show that with this method, both LTE and Wi-Fi systems can co-exist without significantly affecting each other's performance [25].

5.2 Non-contiguous Channel Aggregation

Shared spectrum (i.e. TVWS) will typically be non-contiguous in nature and also vulnerable to increased interference from secondary and primary users.   Therefore, non-contiguous channel aggregation provides a simple and effective means to increase bandwidth and increase reliability through diversity of channels.

5.3 Robust Channel Management

Beyond database approaches to managing TVWS, channel management schemes within the LTE or Wi-Fi RATs are required to assure reliable and efficient operation in typical harsh unlicensed spectrum environments. InterDigital has developed several radio resource management schemes for both the DSM-Wi-Fi and DSM-LTE systems, including: fast channel switching, control channel enhancements to avoid adjacent channel interference, and measurements and sensing to detect both primary and secondary users.

5.4 Flexible and Wideband Radio

Finally, a flexible and wideband radio is required for operation in shared spectrum. If managed properly, the flexibility of sharing a large area of spectrum naturally increases the trunking efficiency. In addition, a radio that can support the simultaneous aggregation and operation of channels is required for both high data rates services and increased reliability. Overcoming challenging design requirements, InterDigital has developed a prototype direct-conversion radio that can span the full TVWS band (~200 MHz), and can aggregate any 4 channels within the band.

6 Conclusions

Spectrum sharing and DSM are promising approaches to provide bandwidth that will be necessary for the huge projected increase in the volume of wireless data. These technologies can provide new alternatives for Wi-Fi augmentation, cellular augmentation and offload, M2M communications, and backhaul/last mile access. Governments, regulatory agencies, standards bodies and industry have recognized this potential as evidenced by the numerous TVWS activities and initiatives to open up other bands for sharing.

There are many technical challenges to harvesting available spectrum and providing robust reliable performance, while respecting the rights of primary users, coexisting with other users, and handling a dynamic interference environment. InterDigital has been actively developing solutions, bringing to bear robust channel management algorithms, non-contiguous channel aggregation, various coexistence schemes, and wideband flexible radios. InterDigital's DSM-Wi-Fi and DSM-LTE platforms have established that technical solutions are viable and can evolve from well-known standardized air interfaces. The DSM prototype equipment has undergone extensive lab and over-the-air testing, and is ready for the transition to develop commercial grade equipment that can open up new frequency bands to commercial wireless networks.

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