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Understanding Dynamic Spectrum Access: Models, Taxonomy and Challenges

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***Abstract*—In last few years, especially after release of the FCC Spectrum Policy Task Force (SPTF)'s seminal report in 2002, we have witnessed growing interest in the field of Dynamic Spectrum Access (DSA) networks. Terms such as reconfigurable networks, Software Defined Radios (SDRs), Cognitive Radios and Cognitive Radio Networks (CRNs) have gained common use. Radio spectrum is a multidimensional entity; space, time, polarization, frequency, power of signal transmission and interference are some of the key dimensions. The static, command-and-control management of spectrum has led to barriers to accessing the spectrum in various dimensions. The notion of dynamic spectrum access can break these barriers in one or more of the dimensions. A review of published research in the technology, policy and legal facets of this broad area indicates that the community is addressing this problem from multitude of angles. In fact, we believe the situation is analogous to story of seven blind men attempting to describe an elephant based on what they perceive when they touch various parts of the elephant. As such, we contend that unless a clear taxonomy of various ways of dynamic access is developed, significant confusion can prevail within the community dealing with these new ways. This paper tries to rectify this situation. It aims to develop a clear taxonomy of various forms of DSA networks, describe in detail various models and identify required technology capabilities, architectural innovations and policy changes.**

I. Introduction

The 2002 report of the Federal Communications Commission (FCC)'s Spectrum Policy Task Force (SPTF) [1] represents a seminal document. It was bold in that it advised FCC to move away from its age-old "command-and-control" spectrum management to a more market-oriented, dynamic approach enabled by rapid innovations in radio communications technology. It rightly observed that spectrum scarcity was the by product of the antiquated spectrum management and though a large part of prime spectrum was assigned, allocated, it remained highly underutilized. In the face of increasing demand for wireless spectrum based services and lack of any new spectrum left to allocate, the task force made the recommendation that FCC develop a spectrum policy that allowed more and flexible access to spectrum. The three main recommendations that concern improvement of spectrum access and efficiency were: (1) Maximize flexibility of spectrum use, (2) Account all dimensions of spectrum use and (3) Promote efficient use of spectrum. The task force also made the crucial recommendation that a clear and exhaustive definition of spectrum rights and responsibilities was central to liberalized spectrum access. Another natural outcome of such liberalized access is the need for efficient and reliable enforcement mechanisms to ensure regulatory compliance of spectrum users.

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The task force report provided a high-level, broad-strokes argument for spectrum management reform but it did not (and may be rightly so) did not articulate specific models of DSA and challenges therein. Several of the new ways of accessing spectrum hinted in this report have heightened possibility of more access to spectrum which coupled with technology progress have led to interest in a new form of networks — the Dynamic Spectrum Access (DSA) networks. Terms such as reconfigurable networks, Software Defined Radios (SDRs), adaptive radio, cognitive radio and Cognitive Radio Networks (CRNs) have become common and often used interchangeably. The radio spectrum is a multidimensional entity; space, time, polarization, frequency and power of signal transmission, interference are some of the key dimensions. The static, command-and-control management of spectrum, which was an outcome of technology limitations of yesteryears, has led to barriers to accessing the spectrum in various dimensions and made it harder to meet increasing demand for wireless spectrum based services. The notion of dynamic spectrum access can break the barriers in one or more of the dimensions and each such "break" and some combination thereof creates a model of spectrum access.

The wireless networks of today can be classified into two broad classes: (1) cellular, infrastructure based networks characterized by a entity called base station providing a centralized switching point for communications from devices in a geographic area. (2) peer-to-peer or ad hoc networks where communicating nodes do not rely on a centralized node. The cellular networks themselves can be of one of the many types, such as pico/femto cells in homes, micro-cellular WLAN hotspots and wide-area/hot-zone area cellular networks. Peer-to-peer networks have found applications in military, public safety communications and even in body area, personal area networks. A new form of all-wireless networks called mesh networks that are a hybrid of cellular and peer-to-peer networks have also emerged in recent years.

The notion of DSA applies to all these forms of networks and leads to different models. A quick study of published research in the broad area of DSA networks indicates that the community is addressing the problem from multitude of angles. In fact, we believe the situation is analogous to story of seven blind men attempting to describe an elephant based on what they perceive when they touch various parts of the elephant. As such, we contend that unless a clear taxonomy of various ways of dynamic access is developed, significant confusion can prevail within the technical, policy and economic community dealing with these new ways. This paper tries to rectify this situation. It aims to develop a clear taxonomy of various forms of DSA networks, describe in detail various models and identify required technology capabilities, architectural innovations and policy changes. It straddles the boundary between policy and technology domains and provides a view of current state-of-the-art in realizing these models.

A. Outline of the paper

The rest of this paper is organized as follows: Section II describe in details the basics of spectrum and outlines five different spectrum access barriers that are an outcome of existing spectrum management. Section III outlines the four broad classes of spectrum access methods. In Section IV describes the *Exclusive Use* spectrum access method and outlines two subclasses, namely long term and dynamic exclusive use. Section V presents the *shared use of primary licensed spectrum* model and its two variants, the spectrum underlay and spectrum overlay. The *Commons* model and its three variations namely, Open-Access, Managed Commons and Private Commons are discussed in Section VI. Finally, Section VIII presents the detailed conclusions of this paper. A tabular summary of all the spectrum access models discussed in this paper is provided in Appendix VII.

II. Genesis of DSA Lies in Current Spectrum Licenses

The parameters that describe the electromagnetic radiation that underlies wireless communications characterize the notion of radio spectrum. The five key parameters are frequency (f), polarization (θ), power (P), space (region R) and time (T). The power and space parameters are intricately linked. Conceptually, when a transmitter radiates to communicate to an intended receiver (s), specific values are assigned to parameters in the five tuple (f, θ, P, R, T). When multiple transmitters want to share the spectrum and therefore have overlapping values to parameters in the 5-tuple, the "right to transmit" must be passed among the transmitters. Such coordination can be done in space, time or frequency dimension [1] and it is implicitly assumed that all the nodes are "cooperative transmitters" i.e they execute a common coordination protocol and radiate in a common frequency band. Such coordination can be realized using multiple access technologies, which can be broadly classified in two categories: (1) *explicit deterministic* techniques such as FDMA, TDMA, SDMA, CDMA. (2) Random access techniques that rely transmission collision avoidance and detection (e.g: ALOHA, CSMA/CA, CSMA/CD).

These techniques however come into play *after the fact* that such a cooperating pool of devices is established. However, since is spectrum is vast in size, an additional layer of coordination is required to create spectrum bands in which cooperating collection of transmitters can operate via these techniques. The regulatory or policy instruments provide such coordination. One such instrument is the *license* which entitles its owner the spectrum usage rights in terms of three parameters – frequency (f), space (R), and power (P). In the existing regulatory regime, a license also clearly defines the *purpose* for which the spectrum can be used by the licensee. For example, in the USA, the spectrum in the 698-806 MHz is reserved for wide area broadcast television (channels 52-69). Similarly, spectrum in the range 824-849 MHz is reserved for commercial cellular services uplink (mobile handsets to base stations communication).

A spectrum license can be characterized by a tuple (f, R, P, License Owner Id ($OwnerId$), Designated Use ($UseType$), License Duration (Dur)). In the existing regime, a license once awarded sets the values in the tuple to be invariant for a long duration.

Historically, licenses have been awarded in "beauty contest" mode which involved significant lobbying to regulation authorities. Most countries now have adopted market-based approaches such as auctions which are touted offer advantages such as giving license to a bidder who values it the most and raising large one-time revenue for the government exchequer.

Consider existing cellular network providers. Each provider's network can be considered a vertically integrated enterprise where the provider first obtains spectrum license, deploys a cellular network (with preferred technology such as GSM, CDMA) and offers end-user pre-paid/post-paid services. Traditional, wide area cellular voice services typically require 8 Kbps throughput per user. However, the multimedia rich services of the future require ultra-broadband multi-megabits/sec throughput per user, which represents roughly 100 to 1000 fold increase.

Currently, a provider has two main approaches to improve per user throughput. First approach relies on aggressive spatial reuse of assigned spectrum. This involves breaking large cells into smaller cells and deploying more base stations using less peak power. This however, leads to increased capital and operating expense for the providers and potentially increased handoffs for the end-user devices. Also, the time constant over which increased user demand can be met is rather slow – of the order of months or years common in network provisioning. The second approach relies on squeezing greater bits/hz/second from the allocated spectrum. This can be accomplished using higher order modulations and multi-antenna (e.g: MIMO) techniques. This increases signal processing complexity which can be compensated by riding the Moore's law. The gains resulting from this also materialize over long time constants of years devoted in inventing and commercializing such techniques. It is evident that improve per-user throughputs to ultra-broadband levels and meeting rapid demand fluctuations in the network, more spectrum must be accessible to cellular services. The licenses of today provide slow, cumbersome, inefficient spectrum access and in

[1]We do not consider polarization dimension

fact create several barriers to otherwise rapid, efficient and maximum-possible access that is feasible due to emerging technologies.

A. Barriers to Spectrum Access

In the following, we elaborate various access barriers that existing spectrum licensing regime introduces.

FlexUse-Barrier: Existing licenses pin-down the "Designated Use" ($UseType$) of the spectrum governed by the license. For example, analog TV broadcast employing NTSC transmission in 6 MHz spectrum has long been proven to be wasteful and better quality video can be transmitted using digital techniques using much smaller amount of spectrum. In large parts of urban USA, alternate means (e.g: cable networks) for delivery of television programming have rendered on-the-air broadcast a defunct technology. However, rigidity of license terms does not allow the license owner to use the license in any other way. For example, the owner cannot operate a metro-area cellular network and offer a broadband data service to end-user. Similarly, the owner cannot use digital packet based broadcast technology (e.g: IPTV over the air) to effectively pack more TV channels and multiplex them with cellular voice/data traffic.

One example of such lack of flex-use or technology-specific allocation can be found in cellular spectrum licensing. In India, GSM cellular operators currently have 50 MHz spectrum (890-902.5 paired with 935-947.5 MHz) and (902.5-915 MHz paired with 947.5-960 MHz), whereas CDMA operators that run Wireless Local Loop (WLL) service have 40 MHz (824-844 MHz/869-889 MHz). The rationale offered is that CDMA is spectrally more efficient and does not need as much spectrum as GSM, thus rewarding a wasteful technology with more spectrum. Similar situation exists in several European countries (e.g: France, Germany, Norway, Sweden) [2].

It is necessary that licenses be technology neutral or opaque. A license holder should have the flexibility to employ the technology it sees fit to provide the service it deems commercially viable.

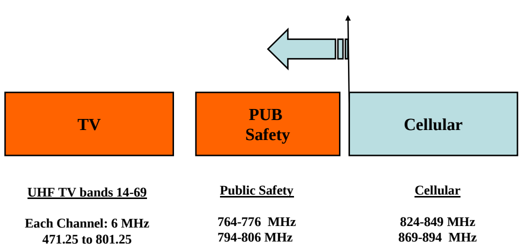

Fig. 1. Spectrum access barrier

Service-Silo barrier: In current licensing regime, specific services are mapped to fixed spectrum bands – the so called "Service-Silos". If the providers of a particular service are under utilizing or not using the spectrum, no other services can be offered in that spectrum leaving it fallow. The examples cited often are the analog broadcast TV bands which are unused in large parts of USA and several public safety services bands which experience low average utilization but infrequent peak utilization. The location of these bands in the spectrum is adjacent to cellular services band (Figure 1) and in absence of the strict "Service-Silo" barriers, these bands can be opportunistically used to offer commercial cellular services.

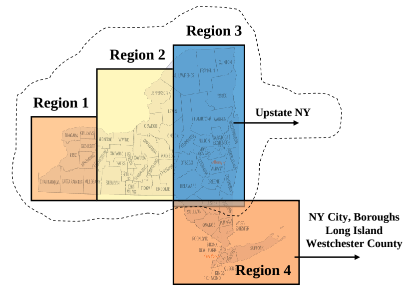

Fig. 2. Spatial scope of current licenses

License-Scope Barrier: Current licenses have large spatial and temporal scope – i.e. they are valid for very large regions and over very long time durations. Consider the scenario illustrated in Figure 2 showing the map of New York state divided into four regions. Approximately, 65% of the NY state population (i.e 12 million out of 19 million) live in the New York City and six satellite counties [2] – Region 4 in Figure 2. The same amount of cellular spectrum is licensed in the entire state – among various Rural Service Areas (RSA) and Metropolitan Statical Areas (MSAs). Clearly, in large parts of upstate New York, a provider may not expand its services or use its spectrum to fullest, leaving it fallow. Unfortunately, the license-scope barrier guarantees that no other provider or a set of devices can use this unused spectrum. Only solution here is to reduce the spatial and temporal scope of the license.

License-Granularity Barrier: Current cellular licenses are for large chunks of spectrum, for example, 50 MHz of spectrum in 800 MHz range (824-849 MHz, 869-894 MHz). There is no way for a provider to acquire smaller amounts of spectrum on small spatial and temporal scale. Such needs often arise to meet traffic overloads in peak periods or in the event of emergencies or hotspots such as big public events (e.g: sports events). As the traffic composition moves from strict 8 Kbps voice to more bursty data traffic with significantly higher per user throughputs, spatio-temporal distribution of traffic in the network will vary dramatically. Using mechanisms such as cell splitting or improved modulations work at time scale orders of magnitude longer than the traffic pattern changes. For example, in a CDMA 1xEV-DO Rev A network, multiple 1.25 MHz carrier channels are configured in a base station to provide service to end-user devices. Each carrier channel provides peak throughput of 3.1 Mbps in the downlink (1.8 Mbps in paired uplink). When a traffic hotspot occurs, the provider should be able to add more 1.25 MHz carriers only in the base stations covering the hotspots (e.g: downtown New York at 5:00pm on a workday, Giants Stadium in New York

[2]Suffolk, Nassau, Westchester, Rockland, Putnam and Orange

for Sunday Football game). Currently, no means exist to do acquire spectrum on such small spatio-temporal granularity.

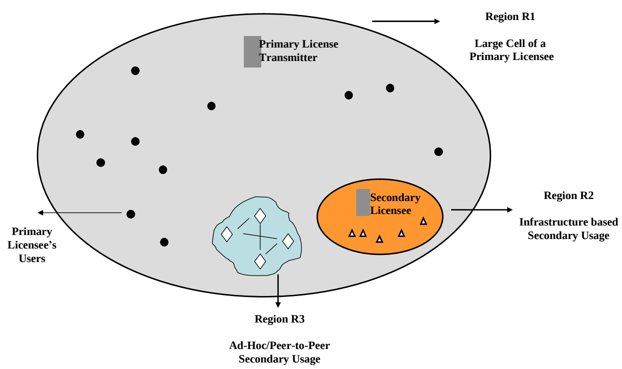

Fig. 3. Secondary usage barrier

Secondary-usage barrier: In the current licensing regime, only the devices owned by the license holder have exclusive rights to transmit. Due to large spatial distribution of these devices, the spectrum usage varies dramatically over time and space. Consider scenario illustrated in Figure 3 showing the large cell of a public safety or a commercial cellular network covering Region R_1. There could be small spatial footprints in the large cell area where there are no primary license users. Current license regime will preclude any opportunistic low-power usage of the spectrum in these areas even though such usage is not detrimental to primary license holder (and its proxy users). Such usage, termed as secondary usage can be in the form of an infrastructure network in a femto or pico-cell with a small base station as in the Region R_2 or a peer-to-peer, ad hoc network of nodes as in Region R_3. We call lack of ability to instantiate such networks that can aggressively use spectrum without undue harm to the primary as *secondary-usage barrier*.

The notion of Dynamic Spectrum Access (DSA) stems from the need to break the aforementioned barriers to flexible spectrum access. Such a notion becomes viable because rapid advances in key enabling technologies used in wireless communications such as high speed digital signal processing in software, wide-band A/D conversion, multi-antenna systems, low power amplifiers, and reconfigurable hardware. For example, high speed digital signal processing enables spectrally efficient higher order modulation technique, multi-antenna processing, digital compensation for RF component non-linearities and even more importantly, degree of reconfigurability in RF parameters. Wide-band RF components and A/D enable transceivers that can operate in wider frequency bands.

III. Taxonomy of Spectrum Access Models

Figure 4 illustrates the taxonomy of spectrum access models consisting of four types:

- **Command and control**: In this model, the regulatory body explicitly lays down the detailed rules for use of the spectrum and assigns it to an entity for use. Often, ownership assignment does not use any market mechanisms as there are no competing interests or entities allowed to seek access to the spectrum. The devices of the entity assigned this spectrum have exclusive and nearly eternal access to the spectrum band. Examples of such spectrum include all bands used for government, military use, radio astronomy and aeronautical operations.
  As regulatory bodies explore increasingly more dynamic access to spectrum, only a small sliver of spectrum will be managed in the command-and-control mode and as such this model is of no interest to DSA practitioners.
- **Exclusive-use:** This model relies on the concept of spectrum band license which entitles its owner exclusive rights to use that spectrum under certain rules. It has two variants: (1) *Long-term Exclusive-use* a model that manages spectrum using space, frequency and type-of-service dimensions and guarantees exclusive ownership with those constraints for prolonged periods of time. (2) *Dynamic Exclusive-use* model that manages spectrum in finer scales of time, space, frequency and use dimensions. The details of these models are discussed in Section IV.
- **Shared-use of Primary Licensed Spectrum:** In this model, the spectrum owned by a licensee (also referred to as the primary user) is shared by a non-license holder commonly referred to as a secondary user. Such sharing takes place without the primary being aware of secondary users i.e. the transmissions of secondary user are expected to have minimal impact on the operating conditions for which primary user devices are designed. This model is attractive as it increases spectrum access and utilization and also, shows promise of co-existing with existing spectrum management. Two possible models of such use are *spectrum underlay* and *spectrum overlay*. Section V elaborates on this form of DSA in greater detail.
- **Commons:** One of the meanings of the word “Commons” refers to “a piece of land for common public use (such as cattle grazing)” indicating a operating model wherein no body can claim exclusive use of a shared resource. The argument that radio spectrum is a public resource that should be equitably and fairly accessible to everyone without undue government regulation is frequently termed as “Commons” model of spectrum access or management. We discuss this model in greater detail in Section VI.

IV. Exclusive-Use Model

In the *Exclusive-Use* model, two variants are possible: the long-term exclusive-use and the dynamic exclusive-use. Since, the notions of exclusive use and license are coupled, we can represent all variants using the license representation (f, R, P, $OwnerId$, $UseType$, Dur) discussed earlier.

A. Long-Term Exclusive-Use Model

Under *Long-Term Exclusive-Use* category, two variants are possible: (1) fixed UseType where the regulator lays down the

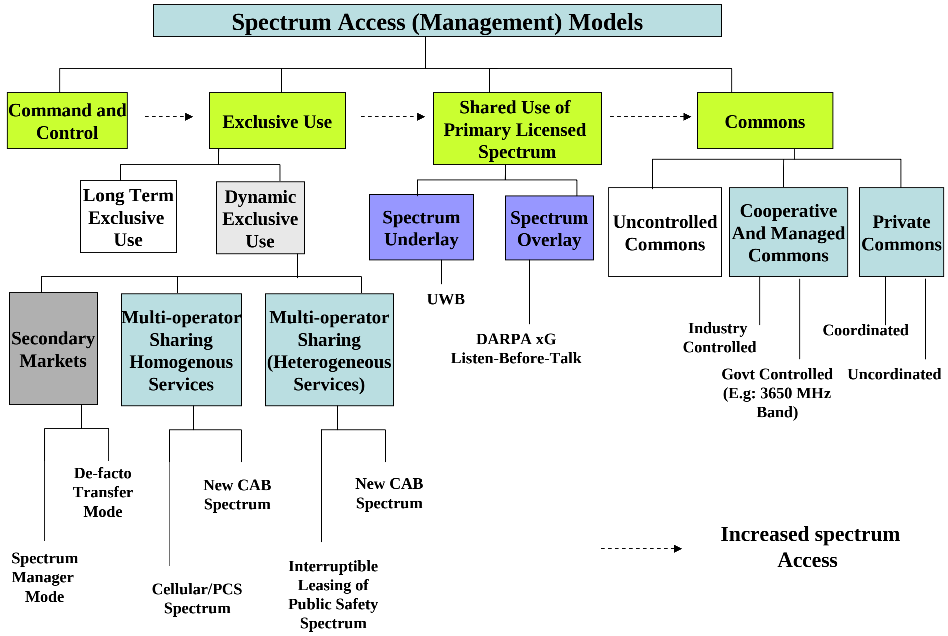

Fig. 4. Taxonomy of spectrum access models

service and technology specific details at the outset and those parameters are invariant during the license duration. This is the norm in current state-of-the-art in several European and Asian countries. (2) Flexible UseType wherein the licensee can change the type of service and/or technology used in the band during the license lifetime. For example, a TV broadcast service operator can eventually change its service to IPTV-over-air combined with a cellular service. This flexibility though appears trivial and inconsequential, breaks the Flex-Use barrier. It can free up a large chunk of spectrum for more aggressive and commercial usage. Though technology agnostic licensing is gradually being adopted especially by Ofcom in UK and FCC, service agnostic licensing is still not a norm.

In these cases, the license owner and the duration of the license never change. The *Dynamic Exclusive-Use* model relaxes these constraints.

B. Dynamic Exclusive-Use

Under the *Dynamic Exclusive-Use* mode, at any given point in space and time, only one entity (operator) has exclusive rights to the spectrum but the identity of the owner and the type of use can change. As such the constraints on (f, R, $OwnerId$, $UseType$, Dur) parameters of the license are relaxed.

The license alterations possible in this category can be carried out using a general mechanism called the *Secondary Markets* (Figure 4)[3]

[3]In the context of securities, a secondary market is defined as a market that provides for the purchase or sale of previously sold or bought options through transactions.

Non real-time Secondary Markets

Regulatory authorities in USA and UK, namely FCC and Ofcom have recently explored measures to promote secondary markets for transfer of spectrum usage rights. In the USA, after the release of SPTF [1], FCC undertook an effort in rule making to foster secondary market. The first report and order and NPRM [3] and the second report and NPRM [4] summarize the current state-of-art in this regard.

FCC offered up two modes of spectrum rights transfer, also called spectrum leasing.

- **Spectrum manager:** In this mode, the primary licensee assumes the role of a spectrum manager and the lessee with transfered licenses reports back to the licensee for all matters relating to the license. The final legal ownership, the responsibility of ensuring lessee's compliance with the original license terms and duties of periodic reporting to the FCC still remain with the licensee.
- ***De facto* Transfer:** Here, the license rights are effectively transferred in total to the lessee. The responsibility of reporting back to FCC and conforming to service and interference rules of the license is entirely lessee's. FCC also introduced two different sets of policies and procedures based on duration of the lease: long term leases exceeding 360 days and short term leases less than 360 days.

There are several interesting things that need to be understood about the FCC's framework.

- **Use restrictions:** The terms of license transfer to lessee in terms of use of spectrum for a particular service are unaltered. FCC allowed license transfers for any spectrum band that employs exclusive licenses but requires that lessee use it for the same service for which original license was issued. As an example, a TV spectrum license cannot be used by lessee to offer cellular service. This is inevitable as FCC cannot create an unfair situation of allowing potentially more lucrative use opportunity for lessee which current licensee cannot avail. In this sense, the FlexUse-barrier remains in place.

  In case of short term de facto transfer leases, the use requirement is somewhat relaxed in that the spectrum that is other wise licensed for non-commercial purpose can be used for commercial purpose for the duration of the lease. Such leases will not be converted to long-term transfer at the end of the lease period.

- **Construction/performance constraints:** Some license have specific construction/performance requirements which requires the license holder to show progress on infrastructure and service deployment and extending coverage to a certain percentage of population. In the spectrum manager and long-term de facto transfer modes, the activities of lessee can be counted toward meeting these objectives.
- **Decimated sub-licenses:** The lease agreements can be for any amount of spectrum, any amount time, and in any geographic area within the scope and terms of the license. This suggests that the licensee can decimate license in spatio-temporal scale to any granularity that it deems practical and lessee's have interest and thus, break the License-Scope and License-Granularity barrier.
- **Subleasing:** To allow additional flexibility to parties in their business arrangements, both the spectrum manager and long-term de facto control transfer leases are allowed to be sub-leased. The licensee can put additional constraints in the sub-lease terms. Also, the licensee can explicitly discourage at its own discretion any subleasing if it desires so by putting restrictions in the original lease terms.

Though, FCC's lease approval process is purportedly streamlined [3, 4], it is still a non real-time, slow process. In case of spectrum manager leasing, for leases less than a year, licensees must provide a notice of lease at least 10 days prior to closing of the lease. For other long term ones, the lease must be notified to FCC 14 days in advance of execution and 21 days in advance of operation. In case of de facto long term transfer, petitions from public parties to deny such lease can be submitted within 14 days and then the lease can stall until review completes. In essence, the FCC's emphasis on meeting public interest objectives and existing license definition make any real-time transfer impossible. Also, coordination, license transfers and market mechanism involve human elements and are not carried out via machine-driven protocols or processes. As such exclusive-use spectrum rights transfer among operators over small spatial, temporal footprints are difficult to achieve in FCC framework. In the following, we describe this scenario in greater detail.

C. Homogeneous Multi-operator Sharing via Real-time Secondary Market

We will describe this model in the context of current commercial cellular services in the USA. The frequency bands these services use are 800 MHz bands (Figure 5) and the broadband PCS 1.9 GHz band (Figure **??**). The 800 MHz band consists of 50 MHz of spectrum with paired bands: 825-850 MHz (Block A: 825-835, Block B: 835-845, Block B*: 846.5-849 MHz) for mobile to base station communication and 870-895 MHz (Block A: 870-880, Block B: 880-890, Block B*: 891.5-894) for base station to mobile communications.

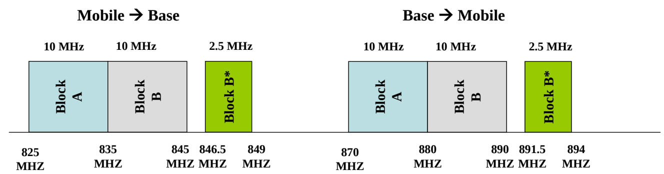

Fig. 5. Cellular bandplan in USA in 800 MHz

Similarly, the broadband PCS spectrum (Figure 6) consists of 120 MHz of spectrum consisting of two bands each of 60 MHz: the mobile to basestation 1850-1910 GHz band and basestation to mobile 1930-1990 GHz bands. Each of the bands is divided into six bands (A, B, C: 15 MHz, D, E, F: 5 MHz).

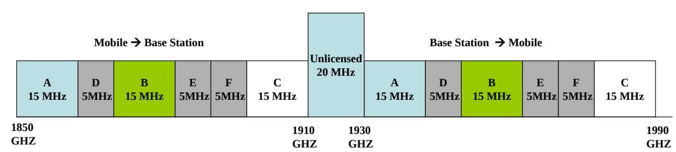

Fig. 6. PCS bandplan in USA in 1900 MHz

In a given geographic region, a cellular provider owns a license to a fixed block A, B of cellular and/or (A to F) PCS bands. Licensing process guarantees that the block assignment is mutually exclusive, thus guaranteeing strict spectrum silos to each provider. Each provider then deploys the base station via a network dimensioning/provisioning process and each base station site is registered with FCC in the Universal Licensing System (ULS) database [5]. The end-user handhelds are proxy user of the provider license in the base station coverage areas. The cellular technology in use may be either old AMPS (30 KHz channels), GSM (TDMA) (with 200 KHz channels), CDMA 1x technology (with 1.25 MHz channel) or W-CDMA/HSDPA/HSPA (with 5 MHz channels).

In a region, the licensed and provisioned capacity for each provider represents a static, peak allocation and the dominant end-user service is still a low and fixed rate[4] voice calls. In absence of large traffic fluctuations, long term provisioning can sufficiently account for expected traffic demand. However, as

[4]We ignore rate fluctuation introduced by audio codecs such as EVRC

the data services become widely adopted, significant variation can occur in traffic demand in a cell on temporal scale, creating hotspots.

If we can provide a means to providers to dynamically access spectrum on spatio-temporal scale, we can enable capacity-on-demand capabilities in the network and efficiently meet rapid traffic fluctuation. Inherent in the notion of such dynamic access is the notion of spectrum sharing among providers and following natural questions arise that need to be answered: (1) What spectrum can be used for such dynamic access? (2) What time constants can such access be supported?. (3) What are costs for such spectrum access and what market mechanisms can be used?. (4) Realizing such sharing requires mechanisms for enabling "Access" to spectrum and "Reversion of spectrum back to the rightful owner". What are technology and policy challenges?.

The answer to the first question affects the answers to the rest. We consider two possible scenarios.

(A) No new spectrum available for dynamic access and sharing

In this case, current cellular, broadband PCS[5] is the only candidate spectrum available for such dynamic access. Consider the following example: In downtown New York, at certain time of the peak hour, congregation of 75 end-users in a single sector of a single cell of a CDMA provider *Orange*'s network want to do video downloads for 10 mins using their EV-DO access at a rate of 500 Kbps/per-stream/per-user. The aggregate cell throughput requirement here is 37.5 Mbps. In current state-of-the art, the provider may have a single license to a 15 MHz PCS block (A, B) and therefore, may have activated up to 11 1.25 MHz carriers. Since, each EVDO Rev A channel can offer peak 3.1 Mbps, in theory, 11 carriers are insufficient to meet the long term sustained demand of 37.5 Mbps. If the provider can "borrow" additional spectrum on-the-fly to activate three more CDMA carriers, it may be able to better meet the demand. Given, no new spectrum is available, Orange may coordinate with another provider RED in the area to see if such carriers are available for temporary lease (access).

To accomplish such sharing across homogeneous providers, following requirements must be met: (1) Existing license need to be decimated to smaller licenses which cover spatial granularity of (approximate) space covered by one or more base stations and are valid for time units of tens of minutes. (2) The license needs to be legally transferable for such time duration. (3) The providers must establish a means to signal their spectrum needs to each other, coordinate access to the license and reversion of license back to the owner from the lessee. The means could take form of a protocol that operates between the network operations centers of providers or in the form of a coordination broker. (4) The providers must cooperate to respect the lease terms of duration and maximum transmit power. The basestation equipment in the provider networks needs to be reconfigurable to limited extent. Specifically, no waveform reconfigurability is required and RF front ends need to operate over the cellular and PCS bands. Since, most vendor basestations cover these bands. The major change is for the service provider to detect traffic overload location and the support for required coordination in the base station and the network. (5) Even more important requirement is for the providers to agree on a monetary compensation for such access. Reciprocal access needs to be monitored and accounted.

[5]Possibly can include new 3G spectrum in 1710-1755 MHz and 2110-2155 MHz

One can see that the DSA scenario outlined here faces several hurdles. First, with some application level signaling from the mobiles and network traffic estimation, hotspots could be predicted. However, the coordination among provider though technically feasible requires business cooperation. Second, the cellular spectrum and networks that use them are results of billions of dollars of investment and engineered for a certain Quality of Service (QoS). It is generally believed that cellular spectrum is highly strained (utilized) even though utilization does vary over spatio-temporal scale [6]. Given the homogeneous nature of service, the user and therefore network traffic behavior follows similar patterns in all provider networks. In such situation, periodic release of spectrum to competitors may be feasible on only small time scale and though such sharing can be engineered, the spectrum acquisition probability drops rapidly if the duration of access capacity addition is long. The incentive for service providers to adopt this approach to hot spot alleviation by capacity addition may not been sufficiently large for incurred complexity and perceived uncertainty in meeting service obligations during leasing time periods. Such model may work especially in low-load and semi-urban conditions.

(B) New spectrum available for dynamic access and sharing

In this case, first outlined in [7], the existing cellular/PCS licenser regime remains intact i.e the license owners continue to have exclusive rights to their spectrum and may optionally share using the model (A) above at their own discretion. The regulatory authority will allocate a *new band of spectrum* that is designated a priori for dynamic sharing. By design, this new spectrum can be allocated in spatio-temporal scale in small units of B Hz and can be exclusively owned for a short duration of T units (mins or hours). We envision two entities: one a Spectrum Access Provider (SAP) provider that has exclusive long term license to the spectrum but is mandated not to own any facilities (or radio network infrastructure) and a second set of entities – the facilities or Radio Network Infrastructure Providers (RIP) who do not have any long term licensed spectrum. Whenever a RIP needs to provide service, it makes real-time requests to the SAP for spectrum to be used at a specific transmitter location. If the request is satisfied, the appropriate cellular service based on RIP chosen technology (such as WiMAX, CDMA, GSM) is activated for the duration of the spectrum lease. At the end of the lease, the RIP ceases its transmissions and spectrum is returned to the SAP.

The spectrum access and reversion is thus explicitly controlled by SAP. and therefore, the spectrum band can be called Coordinated Access Band (CAB) [7], In the short term, the candidate spectrum for such CAB shared among RIPs are the spectrum in 700 MHz bands that becomes available after DTV transition. There are several advantages to this choice: The band is co-located to current 800 MHz cellular bands and changes required to RF frontends in base station and mobiles is minimal. Other bands in the 2-3 GHz (e.g: 50 MHz in 3650 GHz band) are also good candidates.

Note that the SAP broker performs dynamic real-time spectrum allocation out-of the CAB band. It may also use dynamic real-time pricing using mechanisms such as combinatorial auctions, peak-load pricing, fixed pricing or some hybrids thereof [8, 9]. Design of spectrum broker in such model faces several challenges: (1) Real-time allocation of spectrum for large number of transmitters for multiple providers is computationally hard. (2) Dynamic allocation and pricing appears to be computationally even harder. Pricing strategies are hard to design as the "worth" of spectrum to the provider depends on time, location and traffic conditions. (3) Access fairness in must be guaranteed as the very intent of CAB is to avoid "big player" syndrome and provide equitable (but "paid for") access to any interested party. (4) Advance reservation of spectrum should be allowed and differentiated in pricing.

The advantage of this model is that the basestations and client devices required can be designed using current technologies. Specifically, the base stations must be capable of rapid reconfigurability at waveform level and potentially use RF front ends with limited band agility if the CAB is spread over multiple bands. Also, new spectrum leasing and facilities-coordination protocols are required.

This model breaks the License-Scope, License-granularity, and Flex-Use barrier but does not break the Service-Silo and Secondary-Use barrier.

D. Heterogeneous Multi-operator Sharing via Real-time Secondary Market

In this model, the spectrum is shared among providers of different spectrum services such as cellular, public-safety, broadcast TV on various spatio-temporal scale. The assumption here is that the facilities-based infrastructure (e.g.: cell towers for public safety, TV towers) is deployed in each allocated and licensed band and operated independently by different operators. When the spectrum of one operator ("rightful owner") is underutilized, another operator of the same or different type can access and use the spectrum. Such use can continue for a fixed time duration or until the "rightful owner" needs the spectrum. For example, in the context of certain services such as public safety, average utilization can be low but in the event of emergency, service availability must be instantaneous and reliable. As such, in this case, shared usage of such spectrum must be interruptible with strict guarantees. Markus et al. [10, 11] and FCC NPRM on Software Defined Radios (SDR) [12] call this the concept of *interruptible or callable spectrum*.

One can conceivably use a centralized mechanism in the form of spectrum coordination server (broker) which communicates with participating operators to marshal spectrum access requests and reversions. The coordination and required communication in this case happens over wireline networks connecting the spectrum server and corresponding clients in the network (e.g: in the Network Operation Centers (NOC)) of the operators.

FCC's NPRM on SDRs [12] introduced a beacon based approach to coordinate the interruptible access to public safety spectrum. Here, the devices attempting to access the public safety transmit only if they receive a periodic *beacon* sent out by the operator of public safety network. Absence of a beacon is treated as lack of "spectrum opportunity" and the device must pro-actively cease its transmission. As such, this mechanism is conservative but compensates well for loss of beacons due to propagation and other fading losses.

The issues of spectrum allocation, pricing and access/reversion coordination protocols discussed in Section IV-C apply equally well to this model. The required basestations and client devices need to be reconfigurable over multiple bands as the bands of operation for different services are different.

V. Shared-Use of Exclusive Licensed Spectrum

Unlike the exclusive-use model, this model is first to explore simultaneous shared use of spectrum wherein there is a primary licensed owner of a spectrum band and multiple secondary users opportunistically share the band. This model of access can be classified into two types: *spectrum underlay* and *spectrum overlay* each of which is described in the following.

A. Spectrum underlay

The spectrum underlay represents a very conservative approach to shared-use wherein the secondary users transmissions are expected to be of such low power that there is no perceptible change in the interference environment of the primary users. This effectively forces secondary user devices to operate at power levels below the noise floor that the primary devices expect for correct operation. However, such restriction limits secondary operation to anything but a very short range – sufficient for small personal area networks for connecting sensors or as replacement for short length cabling. Ultra Wide Band (UWB) which has been widely researched represents one such spectrum underlay technology [13]. Here, the transmissions of the secondary users are spread over a very wide spectrum band using low power, short length pulses (e.g: 10s of pico-seconds). The FCC imposed requirement that transmission be over a wideband of size greater than 500 MHz and with a power limit of -41.3 dBm/MHz which translate to 75 nanowatts/MHz makes the radiation of UWB devices comparable to such as TVs and computer monitors classified as unintentional radiators. This allows UWB to co-exist with current radio services with minimal or no interference. However, this all depends on the type of modulation used for data transfer in a UWB system. Some modulations lead to spectral lines in the power spectral density of UWB signals and thus, cause interference to licensed systems and also, make UWB more susceptible to primary signal. UWB does have interesting applications in medical, vehicular domains (e.g: radar capabilities for collision avoidance), sensors (e.g: asset tracking, location estimation) and short range multimedia cabling application.

The spectrum underlay breaks the Secondary-Usage and Flex-Use barriers but by its very conservative nature is not suitable for most aggressive spectrum use as it limits the type of network configurations.

B. Spectrum overlay

The spectrum overlay model, actively explored in the on-going DARPA xG program [14] and first advocated by Mitola [15], targets for aggressive, opportunistic exploitation of white spaces or spectrum "gaps" in spatio-temporal domain. The simplest operational model of a spectrum overlay is as follows: Given a primary spectrum user with an exclusive use license to a spectrum band, the homogeneous population of secondary users in the overlay which are members of a flat ad hoc network perform following steps:

- **Spectrum sensing:** Each device continually senses the spectrum band of interest to detect presence of primary transmission. If the sensing inference indicates absence of primary, the device estimates that a spectrum access opportunity is available.
- **Coordination with peers and data transmission:** If multiple nodes in the secondary network see the same transmission opportunity, they contend and coordinate their transmissions. The components of spectrum sensing and medium Access for secondary transmissions may be combined into a single cognitive MAC protocol.
  The nodes use a suitable packet forwarding mechanism – either broadcast or a unicast to communicate. However, for unicast forwarding, a fast converging routing protocol, that establishes required routing state information must run on each node. Other problems encountered in ad hoc networks operating in fixed pre-assigned bands such as node authentication, transmission security, broadcast storm minimization, efficient unicast and multicast routing need to be addressed in this context.
- **Relinquishing the spectrum:** During the secondary use packet transmissions, sensing unit in each device continues to sense the spectrum for onset of primary transmission. If such transmission is detected, the secondary devices must cease transmission and "vacate" the spectrum.

In the mechanics described here, the implicit assumption is that all secondary devices agree on the spectrum band they will use. A even more general model of this form wherein, each device senses a wide band of spectrum and inferences white spaces, additional "rendezvous" protocol is required for secondary devices to agree on a band for communication.

This model also has commercial relevance in utilization of unused or underused 700 MHz TV bands in low-range, low-power mode and significant work has already been reported on Feature Detectors, specifically cyclostationarity detectors for these bands [16, 17] for spectrum sensing component.

The recent 2006 Summer demonstration of xG program in Virginia was aimed at proving feasibility of this concept in the context of military bands and in presence of legacy military radios. A lot of the network aspects such as routing, address assignment, authentication and security were either absent in these demonstrations or statically set up. Also, the primary user activity was representative of military communication not of commercial grade high load. The performance measurements also used uncontrolled packet flows instead of flows that require reliable delivery and therefore congestion control. Though these measurements provide early indications of feasibility of such model, the broader questions still need further investigation: (1) Given a certain occupancy of the primary band, what level of performance is possible? If the primary users aggressively use spectrum, as in cellular bands, the probability of a spectrum opportunities being available drops rapidly. This consecutively drops probability of link establishment for secondary users and can drastically affect performance of key protocols such as routing and congestion management, resulting frequent disruptions. Such disruption may be tolerable for a class of delay-tolerant applications [18], but most commercial applications – streaming, web access where ever-increasing performance is the need and performance is often paid for by end-user, it is questionable if such links are viable. (2) At what level do the secondary transmissions of a large number of secondary users can be free especially in a band that the primary paid to acquire. Without transaction cost for accessing spectrum and a part of the aggregate secondary payout passed on to primary, will such a model be viable? If such a payout is to be implemented, it requires cognizance of primary of such shared use by secondaries. (3) Spectrum sensing, band-specific in the short run and wide-band in the long term, has its associated cost and constraints. The additional RF complexity and power implications, may render xG model suitable only for certain mission critical applications or in cases where power constraints are not significant and performance gains are dramatic (as in vacant TV bands).

VI. COMMONS

The commons model of spectrum access has three variants described in the following.

A. Uncontrolled Commons

When a spectrum band is managed using the uncontrolled commons model – the simplest and purest commons of all, no entity has exclusive license to the spectrum band. As such, any one can own any number of devices operating in such a band and the model is therefore, often also referred as "open spectrum access". The current ISM (2.4 GHz), U-NII (5 GHz) unlicensed bands represent examples such commons.

Here, FCC only mandates that the devices conform to a peak transmit power [19][6]. The lack of shackles of spectrum license acquisition and conformance combined with mass produced devices using well known rapidly evolving standards such as IEEE 802.11, Bluetooth, has spurred tremendous growth in small footprint networks (P2P as well as infrastructure based) operating in these bands.

This model provides no right to protection from interference. Specifically, in dense deployments, wireless links operating in unlicensed spectrum suffer from two kinds of interference: (1) *Uncontrolled interference* that results from non-cooperating entities external to the network that use the same frequency band but do not participate in the MAC protocol used by network nodes. For example, microwave ovens, Bluetooth devices operating in 2.4GHz ISM bands interfere with 802.11b/g networks in the same band. (2) *Controlled interference:* This kind of interference results from broadcast nature of wireless links where a transmission in one link in the network interferes with the transmissions in neighboring links. The interference of this kind depends on factors such as the topology of the network, traffic on neighboring links, number of devices etc. Both these interference lead to scenario commonly termed as "tragedy of commons" [20, 21]. a metaphor used for scenario where too many devices over-exploit and therefore degrade the finite sized unlicensed band. Therefore, despite rapid standards specific (e.g: IEEE 802.11n) technology improvements resulting greater throughput, creation of reliable, revenue generating services in unlicensed spectrum continues to be less than viable due to this weakness.

B. Managed Commons

The notion of *managed commons* represents an effort to avoid the tragedy of commons by imposing a limited form of order or structure to spectrum access. According to some, "open access" model should not be considered a commons and incorrectly doing so as has been in the literature is termed "opens-commons" confusion [22]. In their viewpoint a commons is a resource that is owned or controlled jointly by a group of individuals or entities and it is characterized by restrictions on who uses the resource, and when and how [22] it is used. The entity or a group of entities that establishes and enforces these restrictions is the controller of the commons. As such the notion of managed commons may be considered as the true commons.

This paradigm enables shared, unlicensed, free use of spectrum by devices using multiple technologies. It is shared because the control of the spectrum is shared among the group of devices. It is unlicensed as no device or its owner owns a exclusive (use) license and free as no apriori payment is required to access the spectrum. In its most complete version, managed commons allows all three operational scenarios, namely P2P/ad hoc, macro and micro/pico cell, shown in Figure 3

[6]See Sec. 15.247 Operation within the bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz. Peak power limit of 1 W, .25 W or .125 W.

Two things are central to use of managed commons as a viable spectrum access technique: (1) A good commons management protocol that encapsulates technology agnostic rules. (2) Reliable, scalable mechanisms that quantify rule conformance of participating devices (entities), perform rule enforcement and dole out punishment in the event of rule violation.

Before, one worries about designing such a protocol, the natural question that arises is who sets the rules that are central to the commons management protocol. The answer that it could be a regulatory authority such as FCC evokes trepidation. The slow moving, long drawn processes of regulatory bodies and their public interest focus often guarantees that the rule making is slow and non-responsive to technology advancements. The best thing a regulatory body can do is to designate a band of spectrum as a "managed commons" but not venture any control beyond minimal rule making such as peak power that devices can use. Any rule making should be left to industry – to the manufactures of communication devices, software and to service providers to develop the rules, the resulting protocol and devices that implement them [23].

Lehr et al.[24] outline following desirable characteristics of a good commons management protocol: (1) Promote innovation in devices, services and business models. (2) *Reduce transaction costs of accessing spectrum*. Here the cost does not always mean monetary cost as in licensed spectrum but the invisible cost that can make the protocol and device behavior certification complex and render enforcement difficult. (3) *Provide mechanisms to modify the protocol:* Such capability is necessary to be responsive to technology changes and to allow evolution of the protocol. (4) *Promote fairness and non-discriminatory access:* The protocol should not create multiple classes of users and provide preferred access to high value users. By definition, non-exclusive and group ownership to spectrum dictates that commons should strive to provide non-discriminatory (i.e. equal) access to all compliant users.

Lehr et al.[24] also propose some basic rules to realize a managed commons with distributed control. The salient ones are as follows: (1) All devices should implement transmit power control and power limits should be set on the aggregate transmit power of a collection of devices rather than that of a individual device. (2) All devices must be capable of transmit and receive which precludes "Transmit only" devices such as TV towers and "Receive-Only" devices such as TV receivers. This allows a feedback loop wherein the transmitter behavior can be controlled to manage interference. It also allows the transmitter to be interrupted to ensure increased sharing. Selective receive-only devices such as (spectrum) sensors should be allowed but they must be able to live with the received interference. (3) Devices should be capable of signaling information (e.g: operational parameters, location, interference) to other devices in their region of operation. The signaling may be implemented using an out-band signaling channel or an in-band one, though the former may simplify coordination. Also, "security, authenticity" of signaling information may need to be guaranteed to ensure the information can be reliably used.

(4) *Contention resolution and resource allocation mechanism*: The protocol should rely on a contention resolution mechanism that is standards agnostic to manage contention to access the spectrum.

Lehr et al.'s work represents a good early start; it builds road-signs but not quite the road. We believe making managed commons work poses very tough challenges. To begin with, managed commons represents a "socialist" idea where everyone takes just the right amount and equal amount, does not seek specialized treatment, and cooperates without greed [25, 26]. It relies on a civil society of devices that follow "Etiquette rules", trust each other and cooperate with other devices to ensure interference does not grow to debilitating levels.

The key component of managed commons for spectrum is the enforcement of commons rules, which is extremely hard to achieve. Reliable detection of misbehavior is challenging but even more difficult is the quarantining of a misbehaving device. In wireline networks, detection of misbehaving nodes and isolating them by using packet filtering and network hierarchy can be accomplished. In case of wireless networks, inherent mobility of nodes makes quarantining difficult and requires complex geo-locationing technology. In the worst case, it literally requires physically finding and disabling a device by human intervention. Also, a completely distributed spectrum management riding on a fully distributed trust and security management points to a complicated protocols.

In the event of changes to commons management protocol, scenarios will persist where heterogeneous devices with differing version of protocol run together. In such a case, commons may have to scale down its operations to account for device with lowest capability and achieve sub-optimal performance.

Devising a contention resolution mechanism that accounts for devices with heterogeneous power levels co-existing in a commons is very hard. Simple mechanisms such as "Listen-Before-Talk" are known to work only in limited scenarios and are fraught with hidden node problems leading to unfair spectrum access and performance degradation.

In a exclusive use license system, the license owner and access controller internalize the cost of coordination, enforcement and have legal recourse and opportunity of reward in the event of violation. A managed commons does not offer any such recourse as the ownership is amorphous and often dynamic to a ever changing group of owners. Without a clear deterrent in place, motivation and ease of abuse can't be overstated. In fact, any enforcement mechanism can be thwarted by a competing enforcement mechanism of colluding users who can exclude compliant users. Since, the pet theme of this paradigm is "minimum government regulation" and "industry driven development of commons protocol", it is not hard to envision multiple factions each consisting of their own group of industry pushing their protocol as standards. In absence of some command-and-control rule making, each group will have equal right to claim access to spectrum. In general, it is not hard for scenarios where the managed commons suffers the same "tragedy" that befalls open access.

The enforcement in such commons is intended to be achieved by two means [22]: proactive requirements and reactive enforcement measures. Proactive requirements include the rules imposed but also mechanisms to ensure rules are observed. The problem with distributed ownership is that the early entrants will put in *strong enforcement* mechanisms to deter misbehavior of new entrants. Also, initial entrants may be required to spend resources accommodating subsequent entrants and thus accept the prospect of gradually losing resource share and pull back on any customer guarantees that can be made. This may deter early adoption as pervasive uncertainty will curtail private investment in the networks. The reactive enforcement in licensed bands is easy as the violator and violated entities are very clear. It is hard to establish these parties explicitly in managed commons and in absences of clear definition of interference limits and "what rights are available the violation of which is punishable", slow punishment if any at all will be meaningless.

Lehr et al. also assume that the spectrum available for access via managed commons is plentiful. Since, they advocate a large part of spectrum to be accessible via managed commons a transition mechanism is necessary. One of the recommendations authors make is that a big-bang start wherein a large part of spectrum is abruptly transitioned to the commons mode. These assumptions appear to be non-pragmatic.

Example: Managed commons in 3650 MHz band

Recently, FCC was engaged in rule making to create a 50 MHz block in 3650-3700 MHz to be designated as a a (government controlled) commons [22].

As a part of addressing the 1993 US Government mandate to transfer 200 MHz of federal government spectrum for private use, the 3650-3700 MHz band was slated for transfer in 1999. The band was designated as a mixed-use band as the government would share the band usage with private parties in certain installations around the country.

After its slow long drawn process of rule making, in April 2004, FCC issued a NPRM to designate the band for unlicensed use with the aim of helping rural Wireless ISP (WISP) to introduce new advanced services. However, there are several facets of this NPRM which point to a government controlled managed commons:(1) The peak power limit for the band was set to 25 Watt EIRP much higher than ISM and U-NII bands. (2) FCC also mandated that some form of "contention based protocol" technical requirements of which are left to industry to design must be used in this band. (3) FCC proposed an interesting concept of "non-exclusive license" to essentially monitor number of devices operating in the band. Since, the license is non-exclusive, any number of them can be granted. However, the license holders must register their devices in a common database, consult this database before seeking authorization for new base station (transmitters) and *make every effort* minimize the interference. (4) Only base-station enabled mobile devices are allowed to operate in the band.

This example model of managed commons suffers from glaring problems. FCC mandate of contention based protocol precludes any other potentially better spectrum access protocols. The band terms also eliminate peer-to-peer usage common in ad hoc and mesh networks. In case of unlicensed ISM, U-NII bands users of spectrum provide enforcement within their own private domains (such as home, hotels, offices) in terms of inference control. However, as soon as these networks and similarly networks in 3650 MHz bands are deployed in shared domains (e.g.: outdoors) voluntary interference management is a challenge. These effects of non-exclusive nature of licenses can be compensated by voluntary coordination, though such coordination is not mandatory.

Recently, several parties have filed petition for reconsideration to 3650 MHz NPRM requesting that the band be allocated using a hybrid model: flexible exclusive licensed use in the top 50 metros and non-exclusive licensed use in rural areas. Clearly, this model breaks the Flex-use barrier but wants to retain exclusive-use model in certain geographic areas which in our opinion is not necessary if the the dynamic spatio-temporal exclusive model in Section IV-C is used.

C. Private Commons

Private Commons is a new concept introduced by FCC in its Second Report and Order and Second Further NPRM on elimination of barriers to development of Secondary markets for spectrum[4]. This concept is aimed at allowing use of advanced technologies (e.g: Frequency agile radios capable of listening to coordination channels or of spectrum sensing) that enable multiple parties to access the spectrum to be gradually employed in existing licensed bands at the discretion of license holder. It is a policy mechanism for creating a managed commons where the ultimate ownership of the licensed spectrum is still centralized with the license holder. The responsibility of setting rules for access by other devices not participating in primary use of the license and enforcement of those rules is entirely with the license holder.

There are two ways in which the private commons may be realized in the existing licensing paradigm[4].

License holder offers private commons service

For example, a cellular license holder may specify the technology and protocol and the required hardware, software for devices that want to opportunistically use the licensed band. Such opportunistic usage may happen in two ways. In first case, these devices may be designed to receive and honor “control” commands from the primary licensee’s network. The commands may “signal” spatio-temporal white spaces that the devices can exploit and can be implemented using a control channel - e.g: pilot and auxiliary control channels in current cellular standards or a new cognitive pilot channel emanating from infrastructure base stations.

More complex devices approved by the primary licensee may do the “detection” of access opportunities by spectrum sensing methods without the cost of any infrastructure changes. This mode resembles *Shared-use model* in Section V with the some key differences: (1) the protocol and devices opportunistically using the spectrum are approved by the primary, (2) The band of operations is limited to the primary licensee’s bands and therefore, devices need much less frequency agility. (3) There is only one class of devices and they employ pre-approved sensing techniques and coordination protocols. (4) Also, the extent of increased interference this mode can cause can be apriori controlled by the primary.

In this model, the license holder maintains a customer relationship with device owner and may charge a transaction fee for the same. Such a model may be attractive to end-users who may find guarantees provided by the licensed band attractive as an alternative (or in addition) to unlicensed bands that may be overcrowded.

License holder offers spectrum access

In this mode of operation, the primary licensee may not own or deploy any network and does not maintain a customer relationship with end-users interested in access to licensed spectrum. All it does is enter into agreement with one or more device manufacturers, who work with licensee or independently to specify and develop devices to use the license holder’s spectrum. In this case, there is no primary user of license per se. Also, this mode is different than the managed commons scenario, as the license ownership and the terms and conditions of use are still dictated by a fixed rather than dynamically changing collection of entities.

Currently, FCC proposes to restrict private commons to only peer-to-peer communications between devices in a flat network that does not use primary licensee’s carefully engineered network[4]. As such this, mode is suitable for ad hoc and mesh networks. FCC does not specify power limits in this mode and therefore, no inference can be drawn if this model is meant only for low-range use or it can be extended to longer range communications, especially in rural areas.

We can see that private commons is a middle ground; it allows a exclusive use license holder to “get adventurous” to aggressively use its spectrum, potentially for increased revenue stream via per user periodic transactions – a form of a spot secondary market. It eliminates or minimizes the possibilities of over exploitation and provides better guarantees to end-user than in open access. We believe in the long run private commons may be a viable market option.

VII. Summary

Tables I, II summarize the models discussed in this paper.

VIII. Conclusions

With increasing demand for wireless spectrum services, dynamic spectrum management to improve spectrum access and usage efficiency is emerging as an exciting new possibility enabled by advances in radio technologies and opening up of regulatory processes. A large cross-section of on-going research has focused on cognitive radio and cognitive networks, which in our opinion are too broad, often amorphous notions. In fact, dynamic spectrum management is *one of the important applications* of cognitive radio or even a more limited form of reconfigurable, adaptive, frequency agile radio. A real danger

TABLE I

SUMMARY OF VARIOUS MODELS

Model name	Sub-type	Spectrum band	Coordination method	Comments
Command-and-control	N/A	Most spectrum bands	Regulatory authority such as FCC.	Introduces access barriers (Section II-A). Flex-use, Access-barrier, License-scope barrier, License- Granularity barrier, Secondary-use barrier.
Exclusive Use	Static Long Term	N/A	Number of licensed bands	N/A
	Dynamic, Exclusive Use *Case I: Non-real-time Secondary markets* • *Spectrum manager mode* • *De facto transfer lease*	Almost all exclusive use licensed bands of today	Secondary markets lease transfer rule by regulatory authorities (e.g: FCC NPRM) [3, 4].	• Efficient secondary markets must be established. • Some lease modes require explicit licensee-lessee for enforcement of license compliance. • Time duration of lease and lease transfer indicate non-real-time operations • Suitable for existing licenses with large spatio-temporal scope.
	Dynamic, Homogeneous multi-operator sharing	Existing licensed bands e.g: Cellular, PCS	Explicit coordination among operators who are license and facilities owners	• Coordination using machine-driven protocols run over wired networks (e.g: centralized exchange among multiple operators or via pairwise coordination). Same base station technology can be used. • Economic terms for spectrum leasing needed. • High levels of existing band utilization may limit aggregation gains and capacity-on-demand.
		New spectrum band, called *Coordinated Access Band (CAB)* allocated and designated by regulatory authority for explicit sharing (e.g: Parts of 700 MHz TV bands)	• Spectrum Access Provider (SPA) controls access to CAB by different Facilities-providers. Coordination using machine-driven protocols run over wired networks. • Centralized control via spectrum broker.	• Dynamic real-time allocation and pricing (e.g: via combinatorial auctions or peak-load or fixed or hybrids) • Fairness in access must be guaranteed. • Joint pricing and allocation computationally hard. • Basestations with rapid reconfigurability at waveform level. New spectrum leasing and facilities-coordination protocols. Multi-band RF Front ends needed for multi-band CAB. • Enables true ultra-broadband and capacity-on-demand in wireless networks.

exists that the exotic and complex scenarios of cognitive radio operations that are impractical for long time to come but are rich in research problems capture the imagination of researchers. We believe DSA research literature should benefit avoiding use of this term and focus on it as a standalone problem.

Within the realm of DSA, a clear articulation of models of spectrum access and technology and policy challenges therein is required. To this end, in this paper, we first define five different barriers that current state-of-the art of spectrum management impose on dynamic spectrum access. Then we articulate three different models, specifically: (1) Exclusive-use, (2) Shared-use of exclusive-use license, and (3) Commons. For each of these models, we describe in detail various sub-cases, highlight the barriers they break and present the technical challenges they pose.

Some researchers argue for a world where there are no service providers that deploy and manage infrastructure to offer reliable services and all the spectrum will be freely available and managed in distributed fashion in a co-operative commons. We believe this is an entertaining notion that deserves researching but a pragmatic view is that world will continue to be a hybrid place. Even if a single model is proven the best for spectrum management, transition to that overnight via abrupt change is an hypothetical scenario. Therefore, multiple models of spectrum access will co-exist; some make sense in rural settings, some in dense metro area, some for long range, wide-area guaranteed quality communications, some for military, ad hoc, delay tolerant communications. A single model – a one-size fits for all services, economic, and communication scenarios seems to be hard to come by.

We believe that in the near future, to commence the transition to a bold DSA future, regulatory authorities should consider allocating two separate bands of spectrum: One band called Coordinated Access Band (CAB) reserved for dynamic sharing among facilities-based operators of different services

TABLE II
SUMMARY OF VARIOUS MODELS (CONTD.)

Model name	**Sub-type**	**Spectrum band**	**Coordination method**	**Comments**
Exclusive Use	Dynamic, heterogeneous multi-operator sharing	*Option I*: Cross sharing of existing licensed bands used for heterogeneous services e.g: Cellular, Public-safety, TV Broadcast. *Option II:* Newly allocated CAB band	*Interruptible leasing*: Priority access to primary licensee whose spectrum is subleased. Coordination via broker and/or *Beacon* approach [12]. spectrum broker or distributed *Non-interruptible leasing:* Coordination via central broker similar to homogeneous case	• Lack of correlation in service peaks can enable better spatio-temporal aggregation efficiency • Base stations must be capable over multiple bands and reconfigurable. • Economic terms for spectrum leasing need to be established.
Shared use of Primary Licensed Spectrum	Interruptible Leasing	Public safety bands	Beacon-based coordination or coordination via wireline network based signaling between public safety and other facilities owners	• Device conformance to beacon based mechanism must be guaranteed with high probability. • Monetary compensation and/or better network based access for public-safety professional must be guaranteed.
	Coordinated leasing	Newly allocated bands	Via Spectrum Broker	Similar to the homogeneous case
Commons	Open-access (aka Unlicensed)	Unlicensed bands (ISM, U-NII)	No explicit coordination	Serious over crowding and over exploitation of the spectrum. Lack of QoS guarantees to devices especially in long-range, outdoor scenarios.
	Managed commons	**Newly allocated managed Commons Band (CB)** (e.g: 3650 MHz)	Distributed commons management protocol	• Scalable commons management protocol that works for heterogeneous mix of devices and networks • Rule enforcement and detection of violators will be complex if high accuracy required. • No legal recourse for devices with "deviant" behavior as the ownership is distributed.
	Private commons	Licensed bands	*Option I:* Coordination via infrastructure signal *Option II:* No coordination required but devices and their operational behavior tested, approved by the primary licensee.	Commercially viable, technologically feasible option. Provides a premium service to end-users who want some guarantees that unlicensed bands do not provide.

and other a Commons Band (CB) for managed commons based distributed ownership and dynamic sharing. These bands will be allocated to be service, technology and use neutral.

In the CAB band case, market mechanisms in the form of real-time auctions are necessary to enable market driven sharing. Reconfigurable, multi-band radios with centralized broker based coordination as a first step which eventually can give way to distributed coordination represent necessary technology for this scenario. The model can help create capacity-on-demand services in infrastructure networks and fuel ultra-broadband wireless and therefore has tremendous commercial opportunity.

In the CB case, development of commons management protocol and devices that implement and enforce are a critical technology. Allocating a CB band can spur industry interest and develop momentum to standardizing at least a limited form of commons.

The *private commons* implemented in licensed band with licensee control can go long way in helping quality-of-service conscious users affected by overcrowding in open access, unlicensed bands. Design of standardized protocols and devices for this model has strong market opportunities.

The shared-use spectrum overlay model appears to be very useful in limited form for opportunistic use of unused TV bands or highly underutilized bands. However, without significant policy relaxation, unaccounted, free secondary usage of licensed spectrum in this mode may not be legally tenable.

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