

DIMSUNNet: New Directions in Wireless Networking Using Coordinated Dynamic Spectrum Access

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Abstract

Recent advances in Software Defined Radio (SDR), wide band spectrum sensing, and environment aware real-time spectrum allocation [13, 10, 4] show promise of enabling the new paradigm of Dynamic Spectrum Access (DSA) networks. These networks aim to provide dynamic access to large swaths of spectrum which is currently statically partitioned and underutilized. Majority of research in this area has focused on free-for-all, opportunistic methods common in ad-hoc military applications [10, 12, 13, 15, 16].

In this paper, we argue that a simpler, pragmatic approach that offers coordinated, spatially aggregated spectrum access via a regional spectrum broker is more attractive in the immediate future. We first introduce two new concepts, namely, Coordinated Access Band (CAB) and Statistically Multiplexed Access (SMA) to spectrum that form the basis of our work. We then describe their implementation in the new DIMSUMnet network architecture consisting of four elements: base stations, clients, a Radio Access Network Manager (RANMAN) that obtains spectrum leases, and a per-domain spectrum broker that controls spectrum access. We also describe DIMSUM-RelayCluster – a multi-hop all-wireless architecture to illustrate application of coordinated DSA to fixed wireless access and mesh networks.

1 Introduction

In the United States, the Federal Communications Commission (FCC) sets the rules that govern access to spectrum. These rules have lead to reservation of spectrum chunks for specific purposes; for example, 824-849 MHz, 1.85-1.91 GHz, 1.930-1.99 GHz frequency bands are reserved for licensed cellular and PCS services and require a valid FCC license, whereas 902-928 MHz, 2.40-2.50 GHz, 5.15-5.35 GHz, 5.725-5.825 GHz frequency ranges are reserved as free-for-all unlicensed bands. This strict, long-term spectrum allocation (Figure 1) is space and time invariant and

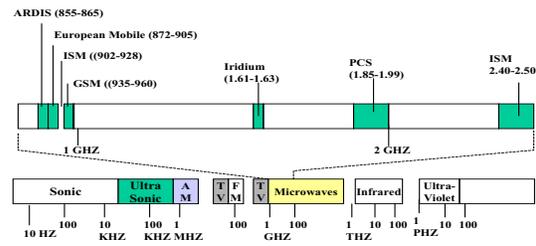


Figure 1. Subset of static spectrum allocation

any changes to it happen under strict FCC control. Regulatory authorities analogous to FCC exist in other countries, (e.g: Office of Communications (OFOCOM) in UK) and similar observations apply equally in their case.

The static partitioning of spectrum has significant operational implications which have been recently brought to light by extensive spectrum utilization measurements in the USA and Europe [3]. First, a large part of the radio spectrum is allocated but barely used in most locations. Several radio bands allocated for military, government and public-safety use experience negligible utilization. The cellular and PCS bands are however quite well utilized but the utilization varies dramatically over time and space.

Often times, technology assumptions that are now antiquated have served as a basis for the amount of spectrum historically reserved for a particular purpose. For example, in case of VHF, UHF bands reserved for television broadcast in the United States, allocation of 6 MHz per TV channel was based on old analog NTSC system even though better quality video can be now broadcast with almost 50 % less spectrum per channel. Given the pervasive penetration of cable-TV, this precious spectrum, though allocated and owned, remains unused in most locations.

On the other hand, unlicensed bands (such as ISM, UNII) which require no spectrum ownership cost, have fueled technology innovation, mass market availability of low cost network and client devices, and rapid network growth. However, often these bands experience significant interfer-

ence due to uncoordinated, aggressive deployment, leading to overcrowding and poor network guarantees.

The current spectrum management methods have left very little spectrum to allocate both for new services and for expansion of existing services, leading to an artificial spectrum scarcity, even though large swath of spectrum remains underutilized. In other words, current spectrum usage is access limited rather than throughput limited [1].

The business implication of current spectrum management is that it has created *purpose built* networks which require capital intensive steps of licensing spectrum, deploying network infrastructure and offering end-user services. Often times high costs and long-drawn process for spectrum licensing have slowed network deployment as evidenced by huge cost-overruns world-over for 3G networks. This has led to big player syndrome where only big service providers can operate networks, stifling competition and fair access.

1.1 Position Statement

We argue that the current spectrum management process must give way to a new approach that breaks down artificial spectrum access barriers and enables networks and their endusers to dynamically access spectrum. In fact, recent technology trends [13, 10, 4] and early policy trends [11] indicate long term feasibility of opportunistic, adaptive access to spectrum, often termed as the new paradigm of *Dynamic Spectrum Access* (DSA). These trends are as follows: (1) *Software Defined Radio (SDR)*: advances in smart, adaptive antennas, high bandwidth A/D conversion, low power amplifiers, fast digital signal processors and inexpensive reconfigurable hardware will make *Software Defined Radio (SDR)* a reality as evidenced by new companies such as Vanu, Inc., and Sandbridge Technologies [4]. SDRs enable on-the fly changes to characteristics of radio such as power, modulation, waveform, and MAC and allow same hardware to be reconfigured for use in different parts of the radio spectrum. (2) *Wideband Spectrum Sensing*: Hardware capable of tuning to any part of a large range of frequency spectrum (5 MHz to 6 GHz) has been demonstrated [10]. Such spectrum sensing enables real-time measurements of spectrum occupancy and inference on underutilized portions of the spectrum. Spectrum sensing combined with SDR and policy specific functions enables the *Adaptive Cognitive Radio (ACR)* that adapts based on its awareness of locale and spectrum. This allows spectrum to be utilized based on real-time sensing and decision-making. (3) The regulating bodies in the USA [11] and European Union [16] are taking initial steps to alter policy to allow experimental networks where spectrum is dynamically managed.

The majority of the research on DSA networks, [10, 12, 13, 15, 16] fostered by on-going ambitious programs such as DARPA XG [2], has focused on free-for-all, opportunistic spectrum access for peer-to-peer ad-hoc communication, typically targeting military applications. A majority of these approaches resort to spectral bandwidth brokering

at the individual node level. However, the complexity in the protocols and the sensing and agility requirements at the individual radio in this case is quite high. Also, its initial utility is limited to homogeneous radio systems[10]. We argue that this is the most ambitious form of DSA. We see

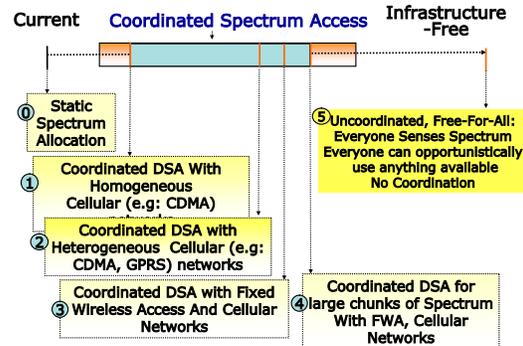


Figure 2. Range of options for DSA

a range of options exist for DSA as illustrated in Figure 2. On this range, the current static allocation represents the left most point, whereas the fully-distributed DARPA XG model represents the rightmost point. In between exist what we call as *Coordinated Dynamic Spectrum Access Networks* wherein the access to the spectrum in a region is controlled, coordinated by a centralized entity called *Spectrum Broker*. As one goes from left to right on the range indicated, the complexity in terms of heterogeneity of networks, amount of spectrum accessed and rapidness of spectrum access increases.

Figure 3 illustrates our model of coordinated DSA for infrastructure based multi-provider cellular, fixed-wireless access and mesh networks. Here the service providers and/or users of these networks do not apriori own any spectrum; instead they obtain time bound rights from a regional spectrum broker to part of the spectrum and configure it to offer the network service. Realization of this model requires new technologies in the form of coordination, signaling protocols, network elements and client devices. We

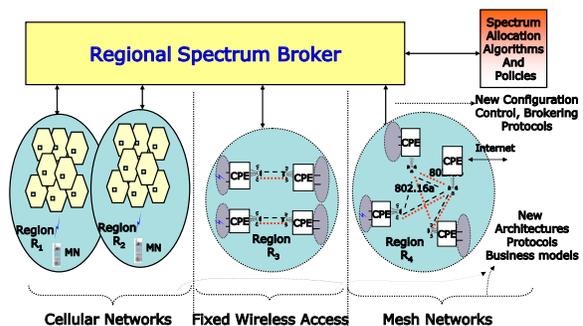


Figure 3. Coordinated DSA model

assert that our model has several impacts: (1) analogous to Dense Wavelength Division Multiplex (DWDM) optical networks wherein activating (lighting) a new wavelength increases bit transport capability of deployed fiber, dynamically adding spectrum enables new kind of wireless networks with bandwidth-on-demand capabilities. (2) Our “as-when-where-needed” spectrum leasing model can enable complete unbundling of service provider market. This will enable new kind of providers and businesses and potentially reduce costs in network deployment and services. (3) From the enduser perspective, this improves spectrum access efficiency and enables true wireless broadband.

In the following sections, we make a case for above assertions.

1.2 Outline

The rest of this paper is organized as follows: Section 2 provides the overview of the three main ideas, namely Coordinated Access Band (CAB), Statistically Multiplexed Access (SMA) to spectrum, and DIMSUMnet. Section 3 describes the DIMSUMnet architecture in detail. Section 4 outlines the DIMSUM-RelayCluster architecture that brings benefits of coordinated DSA to FWA and mesh networks. Finally, Section 5 summarizes the conclusions of this paper.

2 Overview of Our Approach

In the following, we provide an overview of our three main ideas for coordinated dynamic spectrum access.

2.1 Coordinated Access Band (CAB)

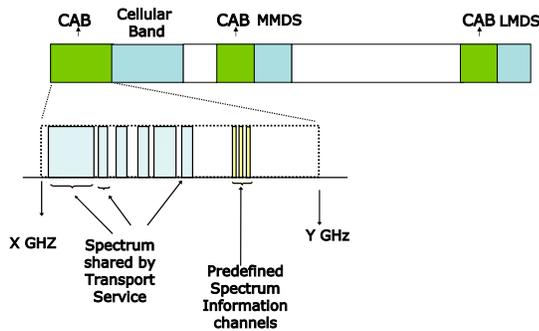


Figure 4. Coordinated Access Band (CAB)

We introduce the concept of *Coordinated Access Band (CAB)*, illustrated in Figure 4, which is a contiguous chunk of spectrum reserved by regulating authorities such as FCC for controlled dynamic access. Multiple parts of the radio spectrum can be allocated as CAB spectrum. The semantics of the CAB spectrum usage is not a priori specified. For

a geographical region, allocation of various parts of CAB spectrum to individual networks or users is controlled by a *spectrum broker*. As such, the spectrum broker permanently owns the CAB spectrum and only grants a timebound lease to the requesters. The lease conditions may specify additional parameters such as extent of spatial region for spectrum, maximum power, and exclusive or non-exclusive nature of the lease. The compliant use of CAB spectrum requires that the “lessee” entity meet power budget constraints all the time and also, “return the spectrum” to the broker at the end of the lease. Clearly, measuring and verifying compliance is a challenge but an infrastructure based approach makes it feasible.

The CAB band resembles a licensed band in that the spectrum lease is a short-duration license. The key differences are: (1) current licenses signify long-term (if not permanent) and sole ownership. (2) CAB leases are awarded by an automated machine-driven protocol. This contrasts the slow, regulatory legalistic process for licenses.

The current unlicensed ISM, UNII bands differ from CAB; there is no “lease” required to use them and no co-ordination mandated. The work on spectrum etiquette servers for unlicensed band devices [14] attempts to provide CAB like coordination which cannot be mandated and enforced. Also, any use of this spectrum is not priced and therefore, is not a revenue stream.

There are two possible models for CAB usage. In the simplest model (CAB-M1), requests for CAB spectrum can be generated only by the network operators. In the more complex model (CAB-M2), the enduser Mobile Node (MN) devices (PDAs, laptops, PCs) participate in the spectrum leasing process and request spectrum for communication with peer enduser devices or with network elements such as base stations.

Within a single CAB, certain fixed frequencies are reserved as SPectrum Information (SPI) channels. In case of simple CAB-M1 model, SPI channels are unidirectional from the BS to MNs, whereas in case of CAB-M2 model, they are bi-directional between BS and MN. The SPI channels are analogous to *Common Spectrum Coordination Channel (CSCC)* proposed in [14] which aims at developing a spectrum etiquette protocol for usage of unlicensed spectrum.

One key question to answer is what part of the spectrum is classified as CAB. We suggest that the CAB bands be co-located with current cellular and PCS bands. Also, unused broadcast TV channels or highly underutilized public safety bands can be designated CAB bands. The current cellular providers will continue to own their licensed spectrum and operate their existing networks unaffected. However, they can deploy or use new networks that dynamically obtain and configure spectrum from CAB bands. When their existing network experiences overload situation, the CAB band network which appears as yet another cellular network can add new capacity. This can improve cellular data and voice services and translate into cost savings for cellular providers,

who otherwise need to split existing cells into smaller cells and install new base stations.

When CAB bands are located adjacent to existing LMDS and MMDS frequency bands, they can help compensate for channel impairments and load surges, and enable enhanced broadband access and backhaul services common in the fixed wireless access networks.

Advantage of co-locating the CAB with existing cellular, PCS, LMDS, and MMDS bands is that changes to the radio components in the client and network elements can be implemented using existing technologies as the frequency range covered over which reconfigurable radio needs to operate is not very large. Over time, as the CAB networks and wideband radio electronics and frontends mature, increasingly larger portion of spectrum can be converted to CAB spectrum, thus allowing gradual relaxation of static spectrum partitioning and wide spread use of dynamic spectrum access.

2.2 Statistical Multiplexing of Spectrum Access in CAB

The concept of CAB improves the spectrum access efficiency and fairness, whereas the concept of statistically multiplexed access is aimed at improving the spectrum utilization in the CAB.

Consider current multi-provider cellular networks. The classic cellular base station site provisioning provides a match between available bandwidth and the coverage area/user density product for all times of operations for a single provider. It performs a worst-case analysis at the individual site-level. Figure 5 illustrates the spectral usage at a location (x,y) , where two base stations of Network Service Provider (NSP) A and C and one base station of NSP B operate. It shows the spectral usage due to individual provider signals and their aggregate as waveforms varying over time. If we consider time period (t_1, t_2) , the spectral utilization of provider B peaks whereas the provider A and C use much less spectrum. Clearly, even though the per-provider usage at (x, y) varies dramatically, the current cell-site analysis will allocate a peak spectral bandwidth of P units per site. Therefore, in our example, 3P units will be used instead of actual instantaneous aggregate usage across all providers. This situation is analogous to using a transmission channel with constant capacity of R bps for a variable data rate streams whose rate varies over $[0..R]$ bps. Although the current site provisioning optimizes the number of base stations, it actually is sub optimal in spectral bandwidth utilization. In this case the most efficient use of the spectrum is either to 1) have a single service provider use all spectrum in a location or 2) have uniform spectral usage in space and time. Neither condition is a feasible option.

Now consider the scenario where the spectrum utilization requirements can be aggregated across multiple service providers and across multiple cells. If the spectral bandwidth requirements of providers are spatially and tempo-

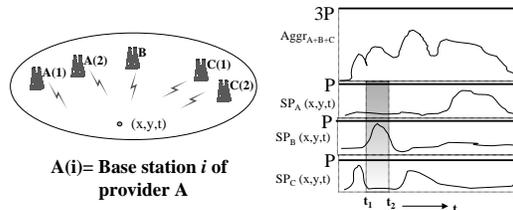


Figure 5. Spectral utilization in multi-provider cellular networks

rally uncorrelated, the aggregate demand will be less than total of peak demands. As such, the most efficient use of the spectrum is to have the aggregate use at a particular region to be constant. The aggregation effect can significantly reduce the required spectrum necessary for a region while maintaining the independence and competitive business characteristics. We call this mode of operation as *statistically multiplexed access to spectrum*.

In above discussion, we did not distinguish the kind of service a NSP provides. Clearly, services such as emergency response, public safety, telemetry, cellular data and voice, fixed wireless access and mesh networks have different temporal and spatial use characteristics. This suggests sharing of spectrum bands among these services has strong potential for statistical multiplexing gain. In fact, even among providers of homogeneous services such as cellular, significant lack of correlation may exist over smaller spatial and temporal scales. Therefore, opportunities may exist for statistical sharing even within such single-use spectrum bands.

This concept can be extended to all dynamic spatial footprints of base stations in dense configurations inclusive of smart antennas. Such a configuration would be closer to creating uniform usage patterns across these aggregate regions and thus a more efficient spectral use. It also allows an NSP to use more spectrum and dynamically add capacity during peak loads and offer better quality-of-service to endusers.

2.3 DIMSUMnet: An Implementation Architecture for Coordinated DSA

The acronym DIMSUMnet stands for *Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile-access network* and is inspired from the model on which popular Chinese eateries operate. The DIMSUMnet implements statistically multiplexed coordinated access to spectrum in the CAB band. It uses a centralized, regional network level brokering mechanism that aims to significantly improve spectrum utilization while reducing the complexity and the agility requirements of the deployed system. In the following, we describe the DIMSUMnet architecture in detail.

3 DIMSUMnet Architecture

The main components of the DIMSUMnet cellular architecture (Figure 6) are: (1) a Spectrum Information and Management (SPIM) broker, (2) a radio access network (RAN) consisting of new type of base stations, (3) a RAN manager (RANMAN), and (4) new intelligent enduser devices. DIMSUMnet employs two new control protocols: (1) SPEctrum Lease (SPEL) protocol involving three entities: the SPIM broker, the RANMAN and the BS, and (2) a SPectrum Information Channel (SPIC) protocol between the BS and the enduser devices over the SPI channels in the CAB band.

In the simplest CAB-M1 mode of DIMSUMnet operation, the enduser devices do not participate in the spectrum leasing (recall Model CAB-M1 in Section 2.1). In this case, the basic operation is as follows: When a base station (BS) in the RAN boots, it registers with its designated RANMAN. The RANMAN negotiates a lease with the SPIM broker for an appropriate amount of spectrum. If the lease is successfully obtained, the RANMAN configures the leased spectrum in the base station, which in turns configures its devices to offer the application services for voice and data. This secure three party interaction resulting in negotiation and instantiation of spectrum lease forms the core of the SPEL protocol. The BS broadcasts or multicasts the spectrum information snapshots received from the RANMAN to the clients. The clients use the information therein to select the application services. This information dissemination is the core function of SPIC protocol.

In the advanced CAB-M2 mode of operation, the SPI channels are bidirectional and the SPIC protocol allows MN to request BS to acquire spectrum and on-the-fly configure a traffic channel between them for a certain time duration. Such capability is useful when enduser would benefit from extra bandwidth, for example, when it wants to transfer short burst of large data (files, video). The BS aggregates such demands from MNs and forwards them to the SPIM server via the RANMAN.

In the following, we describe the components in greater detail.

3.1 SPIM Spectrum Broker

The SPIM server manages CAB spectrum rights and propagation of information about those rights to any entity interested in using the CAB spectrum in a given geographical region R . It manages all dimensions of the CAB spectrum, namely frequency, time, space (location, direction), signal (polarization, coding/modulation) and power. The basic tenet of DIMSUMnet spectrum usage is that any use of CAB spectrum not approved by SPIM server is a non-compliant usage.

The SPIM server maintains a complete topographical map of the region R which records position of all base stations and approximate extent of cell coverage associated

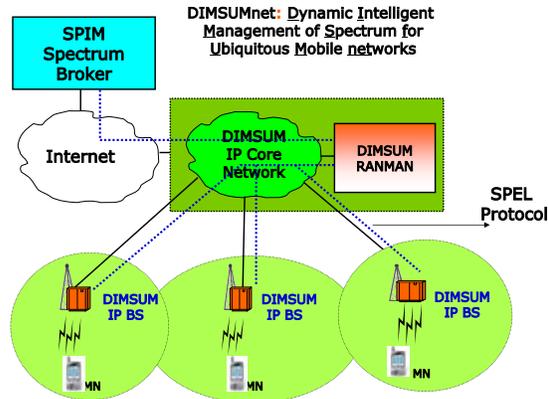


Figure 6. DIMSUMnet architecture

with each BS. For every cell, it maintains a *spectrum snapshot* [15] that records: (1) spectrum used for SPI channels and (2) a spectrum allocation map (SAM). Each SAM entry records spectrum parameters such as (a) start and end of spectrum band, (b) network service provider (NSP) it is allocated to, (c) the current waveform or network access method (e.g: GSM) used in the spectrum, (d) time duration of lease, (e) maximum transmission power allowed, and (f) optionally, information about interference due to thermal noise and other sources such as secondary users. The SAM changes with time as the various parameters in SAM entries change. For example, when the SPIM server de-allocates a spectrum, the corresponding SAM entry is removed.

Note that in a deployed DIMSUMnet network, given the critical nature of spectrum resource, instead of a single SPIM server per region, multiple SPIM servers must redundantly maintain consistent information. In this case, if one of the SPIM servers fails, one of the remaining servers can still satisfy spectrum lease and information requests in a region. We call this mode of operation where a cluster of SPIM server provides redundant oversight for a region R as the SPIM Overlay. We need to examine a scalable mechanisms such as application-layer multicast and distributed hash tables (DHTs) to minimize overhead of frequent and deterministic dissemination of spectrum snapshot information in the overlay. Also, a loose interaction among SPIM servers serving overlapping regions may be necessary to minimize interference.

The overhead of spectrum brokering increases as the number of cells in a region increase. This scenario would be common when a region is composed of a large number of micro-cells (each with range of 100s of feet) and pico-cells (each with range of 10s of feet). It is unrealistic to expect the base stations in such cells to acquire spectrum leases from a remote SPIM server. Also, in most cases, these base stations are inexpensive, simple devices that support a fixed radio technology (analogous to 802.11 WLAN or Bluetooth operating in CAB band) and may not support spectrum information channels. In this case, a hierarchy of

SPIM servers, where servers in the lower levels in the hierarchy are responsible for smaller geographical areas, will be required.

3.2 RANMAN

The Radio Access Network Manager (RANMAN) is a new network element, which controls spectrum leases for several DIMSUM base stations. It is aware of the static characteristics of the base stations, specifically hardware and software capabilities of ACRs such as the supported radio frequency range, signal processing and various waveform (CDMA, OFDM, specific modulation etc.) capabilities, maximum power. It also keeps track of their dynamic characteristics such as current load, power usage, available power etc. Based on location specific policies, base station characteristics, and geographical coverage requirements for service provider, it estimates the amount of spectrum required to meet and sends bids to the SPIM server. If the spectrum leases are granted, it sends commands to the base stations to configure their ACRs as per the service provider specific MAC and radio protocol and thus, activates radio access channels. It periodically renews existing leases or terminates them. It may renegotiate new spectrum due to reasons such as price changes, increased interference in existing band, and increased load reported by the base stations.

3.3 DIMSUM Base Station

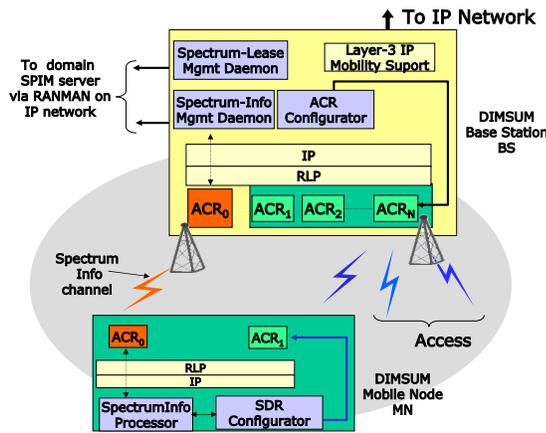


Figure 7. DIMSUM-BS and DIMSUM-Client

Each DIMSUM-Base Station (DIMSUM-BS) (Figure 7) contains multiple instances of ACRs out of which a subset are reserved for SPI channels and others are used to provide access channels for bit transport service for enduser traffic. Each BS can be either static or mobile and uses one of the ACRs periodically configured as a GPS receiver to know its exact location.

Each BS contains two daemons that implement protocols related to the spectrum management:

- **Spectrum-Info daemon:** This daemon communicates with the domain SPIM server to obtain spectrum-map snapshots relevant for its location and broadcasts it over the reserved SPI channels. It also collects information such as number of endusers using each chunk of spectrum, per user information such as geo-location, SNR for the current wireless access channel etc. and propagates all or aggregates of this information to the SPIM server.
- **Spectrum-Lease Daemon:** This daemon communicates to the Radio Access Network (RAN) manager, to obtain spectrum leases and commands to configure its ACR devices. The commands specify the frequency bands, power and type of waveform to be used. For example, the command may specify using max power of 30 watts, a carrier frequency of $X = 1.923$ GHz, bandwidth of $B = 1.25$ MHz with CDMA Direct Sequence Spread Spectrum (DSSS) waveform. If the ACRs are successfully configured, the daemon registers with the RANMAN its use of the spectrum chunk and the associated parameters. In the event spectrum lease expires and the RANMAN does not send a lease renewal notification, it disables ACRs and notifies SPIM server of the de-allocation of spectrum chunk. It also notifies the Spectrum-Info daemon of this event to ensure spectrum snapshot propagated to enduser is appropriately adjusted.

We envisage DIMSUM-BS to be an IP-aware base station which implements various protocols, namely: micro/macro mobility protocols (e.g: Mobile IP, MobileNAT anchor node[8]), address management (e.g: DHCP, NAT), AAA protocols (e.g: RADIUS), and QoS support (e.g: Diff-serv packet labeling, class-based QoS).

3.4 DIMSUM Client Device

The DIMSUM client device contains at least two logical or physical instances of ACR devices, one used as a *control channel interface* and the other as a *data interface*. In simplest (CAB-M1) mode of operation, it uses the control channel ACR to scan SPI channels in the CAB band to obtain spectrum snapshots broadcast by the DIMSUM-BSs in the region. These snapshots enable client software to obtain information on availability of application services in different parts of the spectrum, specifications of the network providers offering these services, layer-1/2 specifications such as modulation, MAC, and other information such as current load, interference levels etc. Based on this information, its own QoS needs, ACR waveform capabilities, and power and location constraints, the client decides on the parts of the spectrum and the application service to use and

configures one or more the data interface ACRs with appropriate radio characteristics. Multiple ACRs concurrently accessing transport in different parts of spectrum enable client to dynamically adjust to variable bandwidth requirements of its applications.

Note that rudimentary forms of a subset of above concepts operating over slow timescales are already used in the current cellular networks. The client devices for these networks maintain a **Preferred Roaming List (PRL)** which is an ordered list of tuples $\langle \text{System ID (SID)}, \text{Network ID (NID)}, \text{Radio Frequency } f \rangle$, where SID, NID uniquely characterize the provider base stations that use frequency f . When the device detects deteriorating radio signal, it consults PRL to decide which carrier frequencies to scan to find service offered by its preferred provider or its roaming partners. The PRL list can be downloaded to the phone dynamically over the air interface using signaling channels [5]. This concept has been successfully employed to achieve global roaming across multi-technology, multi-provider networks [7]. However, in the current network, PRL changes and therefore, such downloads are very infrequent. On the contrary, in DIMSUMnet, the *spectrum snapshots*, which are somewhat analogous to PRLs, may change frequently (e.g.: every few minutes) due to changes in spectrum allocation.

Note that the application service client is accessing may be re-mapped to another part of the spectrum with potentially different characteristics. In this case, the client must detect this event and reconfigure its data interfaces to continue its network and transport protocol connections. The client may also pro-actively reconfigure its data interface to respond to events such as increased interference, loss of signal, reduced service price, need for increased data rates and data rate degradation due to congestion or mobility. During such a change, the client software must support session continuity to ensure seamless enduser experience. Availability of multiple ACR devices allows concurrent detection of spectrum snapshot changes or other detrimental events and reconfiguration of data interfaces.

In the advanced CAB-M2 mode of operation where the SPI channels are bidirectional, the client device may also use a reverse link in the SPI channel to convey to the base-station changes in its bandwidth requirements and request additional spectrum to be exclusively configured for its traffic channels to the BS. The DIMSUM client may optionally contain a spectrum-sensing component, which periodically measures observed power spectral density in a broad range of CAB spectrum or in frequency bands adjacent to current carrier frequency. It communicates both these data and their aggregates periodically to the base station via the SPI channels.

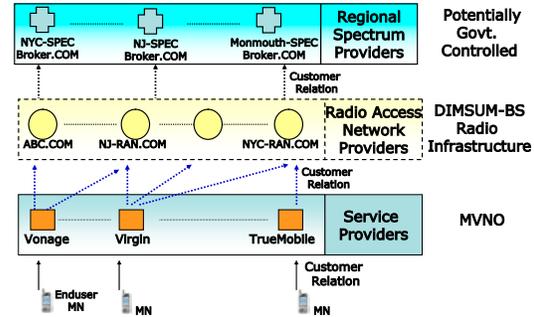


Figure 8. Unbundling the service provider market

3.5 Deployment Models: Shared vs. Non-shared Base Station

In the existing cellular networks, large NSPs (e.g: Verizon) license spectrum from FCC, deploy their radio access networks and sell voice and data services to the endusers. However, this model requires large capital investments and therefore, has led to non-competitive environment that stifles innovation and introduction of new technologies and services. A new form of Mobile Virtual Network Operators (MVNO) (e.g.: Virgin Mobile) that do not own any spectrum and infrastructure but offer application services by leasing services from large providers are becoming popular [13]. However, their growth is still controlled by the primary providers. DIMSUMnet enables new deployment models (Figure 8), specifically *shared base station model* and *non-shared base station model*, which show promise of creating new kind of providers. Common to both these models are the regional or national *spectrum providers* that operate the SPIM server overlays and spectrum brokering services.

Shared base station model In this model, a new form of infrastructure providers called the *RAN providers* own and operate the base stations and the RANMAN but do not own any spectrum. They lease CAB spectrum from the spectrum-providers as an when needed. The application-service providers (ASPs) that offer specific application services (e.g: voice, data) to endusers are the clients of the RAN providers and are essentially MVNOs in the CAB spectrum [13]. As an example, the *fcc-spectrum-broker.nj.gov* can be a spectrum broker network in New Jersey, which has three RAN provider clients *central-nj.ran.com*, *north-nj.ran.com*, *sounth-nj.ran.com* which own and operate radio access networks in the CAB band in northern, central and southern regions of state of New Jersey.

The ASPs only maintain the enduser authentication, billing and roaming agreement databases and do not concern with infrastructure operations and spectrum leasing.

Their services are offered in different parts of spectrum at different times depending on which part of CAB spectrum is leased. If multiple RAN providers operate in a region, an ASP may use one or more of those to offer its services and afford additional service resiliency. This however requires that the RAN providers bid and use non-overlapping frequencies chunks for the same service. In this case, the same ASP's service will be simultaneously available in different parts of the spectrum increasing potential for spectrum utilization and per-user data rates.

This approach also requires mechanisms and policies for appropriate allocation and isolation of base-station resources such as the ACR devices, power budget for radio amplifiers, IP backhaul bandwidth, and transmit power used for each service provider.

Non-shared base station model In this model, the provider that offers the application services also owns and operates the base stations and leases the spectrum required to operate the service. Therefore, each service provider has its own RANMAN and base stations. This model differs from the current cellular model in that the provider still does not statically own any spectrum but leases it dynamically. Offering redundant physical coverage in this model requires the provider to deploy multiple base stations in the same area and therefore it can be capital intensive.

In both the models, the current cellular providers can continue to hold their existing licenses and use their existing infrastructure much the same way. Any new capacity they add in the CAB bands on-demand is accessible to the enhanced enduser devices via the PRL updates in the spectrum snapshots.

3.6 Spectrum Allocation

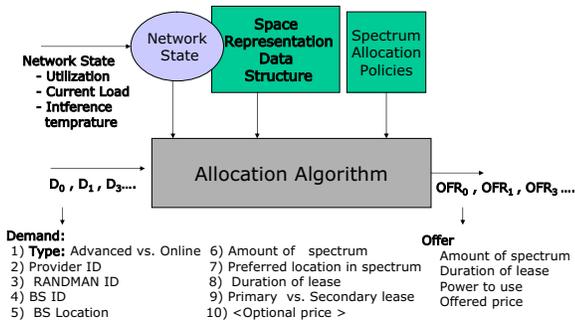


Figure 9. Spectrum allocation model

The spectrum allocation algorithms and policies focus on answering three critical questions: (1) How much spectrum can a provider get, if any?. (2) How long can a requester hold the leased spectrum? and (3) How can a provider win a spectrum bid? At any point in time, the answers to these questions (i.e. rules of the resource allocation) are dynamic, varying over time and location. It is the system's responsi-

bility to determine, state, update, and enforce these rules as system conditions change.

In our model for spectrum allocation (Figure 9), we assume that the spectrum broker receives a series of demands D_i at different time instances. Each demand has a type of reservation which can be either advanced which allows a RAN manager to reserve spectrum much in advance of its actual use or online instantaneous in which case the reserved spectrum is immediately used. Other relevant demand parameters are various infrastructure identifiers (BS, RANMAN, provider ID, BS location) and lease details (amount of spectrum, spectrum location, primary vs. secondary status, duration). The output of the spectrum allocation is an offer OFF_i that is forwarded to the requesting RANMAN. The offer contains amount of allocated spectrum, its location, amount of maximum transmit power, duration of the lease and a price. We advocate a *soft state model* for spectrum allocation, where each lease is for a fixed duration and after the duration expires the lease must be renewed.

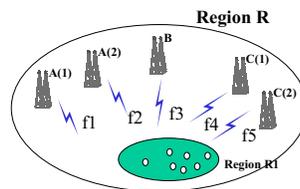


Figure 10. Spectrum allocation and regional interference

The knowledge of the clients' radio environments in a given region can greatly aid the smarter decisions on spectrum allocation. Figure 10 shows a case where users in a region R use the services of several base stations in that region, which are operating in different parts of the CAB spectrum. These users may experience adjacent channel interference caused by uplink transmitters using an adjacent spectrum portion. If the SPIM server allows multiple operators in the same band operate at different power levels, significant variability in interference levels may be observed. However, if end-users periodically collect data on interference observed in the entire CAB or adjacent bands of spectrum they are using, this information can be propagated back to SPIM server via the SPI channels. The SPIM server can then construct a dynamic map of radio usage and observed interference in the region, and use that information for more efficient spectrum allocation. For example, if the interference in a subset of the region (Region R1, Figure 10) exceeds the tolerable level, it may request the RAN manager operating the interfering BS to reduce its transmission power, thus reducing the co-channel interference. Alternately, it may ask its BS to reassign a different part of the spectrum to the users in Region R1 who are experiencing

intolerable interference.

The spectrum pricing may work in two modes: (1) *auction* mode in which each demand (bid) has an associated price and the winning bid decides the final price. (2) *merchant* mode in which the price is entirely decided by the allocation procedure. We believe that utility pricing techniques used in current electric power markets may be relevant to spectrum allocation. A technique of specific interest is the *modified price index cap*. In this method, electric utility tariffs (or bids) rise with inflation (CPI), and are simultaneously forced to decrease by a pre-determined variable, which is based on each company's relative inefficiency. In the application of this approach to spectrum management, the relative efficiency of a service provider can be a dynamic variable that is based on current provider specific and total spectrum utilization.

Different policy methods also should play role in the spectrum allocation decisions. Following is a short list of different policy methods of interest:

Pure CAB vs. (Partial CAB+Cellular): In the pure CAB mode of operation, the entire band is dynamically allocated. This increases complexity of the client devices and signaling and potential of service disruption. However, it increases competition and access efficiency. An alternate model where part of the CAB is converted to long-lived base licenses can improve service quality. The providers that already hold this base license or a license in the existing cellular or PCS bands should not be given first right to dynamically shared part of CAB spectrum.

Cost of CAB spectrum access vs. owned spectrum: The CAB spectrum should be cheaper per time period than owned spectrum. A mechanism is necessary to assure that providers do not abuse the cheaper dynamic spectrum or hoard resources. To this end, a provider must prove that it needs the spectrum when it makes a bid for the CAB band. One way to do this is to use periodic utilization reports from the provider for its existing leases to prove that they are sufficiently utilized to warrant new allocations.

CLEC vs. ILEC status of the lease request: The Competitive Local Exchange Carriers (CLECs) are the emerging service providers that compete with large Incumbent Local Exchange Carriers (ILECs) to provide network access. To encourage increased competition, spectrum allocation may give greater weight to demands from CLECs.

Effect of spectrum allocation history on bids: The spectrum lease history should affect allocation decisions. For example, if a service provider is granted spectrum in a given time period, will it be granted new leases (either renewal of existing lease or completely new spectrum)? A policy needs to be devised that can trade off fair access to spectrum vs. the application service continuity. Disregarding the history and allocating the spectrum randomly can result in rapid re-mapping of application services in different parts of the spectrum, leading to frequent service handoffs (even in absence of enduser mobility) and in the worst case lead to service disruption. On the contrary, *sticky allocations*

that favor providers with already allocated spectrum reduce access fairness.

Access Fairness and Cost Incentive: Pricing must assure fairness and feasibility of such a system. Specifically, the service providers with the most money cannot influence or gain a competitive advantage through monetary disparity with smaller operators.

Clearly, the spectrum allocation algorithm must formalize the policy considerations and combine them with the mathematical formulations of network states and radio environment. Our ongoing work aims to design, analyze, and implement candidate spectrum allocation algorithms for auction and merchant modes of operations.

4 DIMSUM-RelayCluster

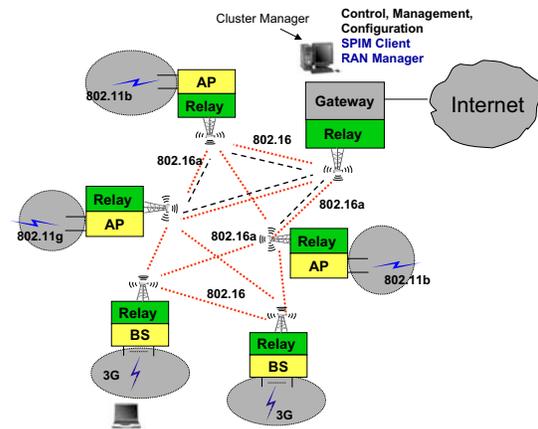


Figure 11. DIMSUM-RelayCluster

The DIMSUM-RelayCluster architecture brings the benefits of dynamic spectrum to Fixed Wireless Access and mesh networks.

DIMSUM-RelayClusters consists of two new network elements (Figure 11): the DIMSUM-Relay and the DIMSUM-Gateway. The relay nodes contain multiple ACR devices, which can be operated in two modes: **access interface** and **packet-relay interface**. The access interfaces are configured to operate as legacy 802.11 or 3G interfaces and are used by the end-user devices for network access. The gateway element contains multiple ACRs, which can be operated in two modes: **packet-relay interface** and **internet backhaul** interface that connects the gateway to the Internet. Note that the backhauls can be wired interfaces such as Ethernet and in that case they are not ACR devices. The packet-relay interfaces are adaptive radio links constructed using dynamic spectrum access in the CAB spectrum. These links may be configured as 802.16 long range FWA links [6] or short-range 802.11 a/g links. They are used to construct a self-configuring, secure, power and bandwidth adaptive multi-hop packet routing backbone that

forwards end-user traffic received on access interfaces to the Internet gateway nodes. The management entity called **ClusterManager** either co-located with a gateway node or implemented as a separate element, implements the RAN manager and SPIM Client functionality. It also implements the SPI daemon, which broadcasts the spectrum snapshots on its relay interfaces.

When a relay node boots, it listens to the SPI channels to discover the spectrum snapshots and the presence of relay elements in the certain parts of the CAB. For example, the snapshot may show that part of spectrum is used to operate 802.16 links (dotted lines in Figure 13) and also provide the current network load. The relay node may configure its ACR to those channels and using Point-to-Multipoint or Mesh mode of 802.16 [6] join the existing links in the relay network. In this case, the relay interface on the gateway node serves as the 802.16 base station. The relay node registers its ACR capabilities with the ClusterManager and also periodically forwards to it information such as its visible neighbors, observed network load and interference levels. The cluster manager thus knows the complete topology of the relay network and the links used in the forwarding infrastructure. If it detects that certain links are getting overloaded, based on its knowledge of relay ACRs, it may decide to configure additional links (shown as dashed lines in Figure 11). Specifically, it may setup additional point-to-point link between pairs of nodes or a point-to-multipoint or mesh link among subset of nodes. For this setup it negotiates spectrum on behalf of the relay nodes using SPEL protocol and then send RAN manager commands to relays to reconfigure their ACRs.

The ability to add bandwidth-on-demand to relay infrastructure makes it possible to alleviate throughput degradations due to congestion, channel impairment and load surges. For example, under heavy load condition when traffic in access interfaces of all relay is high, a large amount of traffic directed to the gateway nodes creates a *funneling effect* where links closer to the gateway experience congestion. In DIMSUM-RelayCluster, such congestion is detected and compensated by adding capacity on links leading to the gateway.

Clearly, the gateway and relay nodes can employ new advanced antennas, dynamic spectrum allocation, and scheduling to improve relay throughput without affecting the client devices in the access networks. The key design problems in this architecture are as follows:

- **Gateway discovery and secure registration protocol:** A newly deployed relay node or a node that reboots must be able to auto-discover the set of gateway nodes in its vicinity based on its own selection criteria such as QoS along forwarding paths, capacity of uplinks at the gateway, current load in the network etc. Once gateways are discovered, relays must perform a secure registration.
- **Auto-configuration:** Multiple relays and gateways

must auto-configure themselves and converge to a stable packet-forwarding infrastructure that makes appropriate QoS guarantees. Auto-configuration involves automatic spectrum and power level selection, neighbor discovery, and configuration of relay forwarding via negotiation of operational characteristics such as addressing schemes, mobility, and forwarding semantics. In the event of node failures (due to power loss), interference, and frequency reassignment, the network must reconfigure itself rapidly.

5 Conclusion

Dynamic Spectrum Managed networks will be a disruptive force that will lead to new form of wireless networks. In this paper, we argued a case for coordinated, real-time dynamic spectrum access instead of opportunistic, uncoordinated methods common in ad-hoc military applications. We introduced the concepts of *Coordinated Access Band (CAB)* and *Statistically Multiplexed Access* to spectrum. We described the DIMSUMnet architecture that implements these concepts for cellular networks using a centralized regional spectrum broker. We elaborated on new control plane technologies in the form of RAN manager and associated spectrum leasing and information protocols and new data plane technologies in the form of DSA aware reconfigurable base stations and client devices. We also highlighted issues in deployment models and spectrum allocation. We also presented the DIMSUM-RelayCluster for fixed wireless and multihop all-wireless infrastructure. The potential impact of our schemes is that they can lower capital expenditures for spectrum acquisition and thereby increase competition and rapid introduction of new cellular and FWA services.

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