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Spectrum Management in Coordinated Dynamic Spectrum Access Based Cellular Networks

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***Abstract*: This paper focuses on spectrum management in next generation cellular networks that employ Coordinated Dynamic Spectrum Access (DSA). In our model, a spectrum broker controls and provides time-bounded access to a band of spectrum to wireless service providers and/or end users and implements the spectrum pricing and allocation schemes and policies.**

We introduce several concepts that are central to the design of spectrum management algorithms. These include: (1) demand processing model (batched vs. online), (2) spectrum pricing models (merchant mode, simple bidding, and iterative bidding), (3) different network infrastructure options such as shared base stations with collocated antennas, non-shared base stations with collocated antennas, and non-shared base stations and non-collocated antennas, and (4) important spectrum management concepts of scope, access fairness, "stickiness" and spectrum utilization. Based on these concepts, we investigate practically realizable candidate algorithms for spectrum allocation for homogeneous CDMA networks.

***Index Terms*— Wireless networks, Dynamic Spectrum Access (DSA), Coordinated DSA, Spectrum management**

I. INTRODUCTION

Currently radio spectrum resource in most countries around the world is statically partitioned into blocks allocated for specific purposes. The semantics of spectrum usage such as maximum power, and type of service (e.g.: cellular, public safety, TV broadcast etc.) are a-priori specified and are location and time invariant. Such rule making has often been based on antiquated technology assumptions and in absence of market mechanisms in place. Also, the current spectrum management process involving primary user licensing or property rights on one extreme or complete unlicensed usage or commons on the other has led to serious implications.

The business implication of this is that it has led to purpose built networks that involve capital intensive steps of acquiring licensed spectrum, deploying network infrastructure and operating and offering end-user services. The process of acquiring licensed spectrum happens to be a slow, long drawn, legalistic process. This has caused a "big player syndrome" where only very large service providers can compete, leading to slow innovation in networks and services as evident, for example, in inordinate delays in the introduction of 3G networks.

Current spectrum management also has serious operational implications: (1) though majority of spectrum is allocated, a large swath of spectrum is highly underutilized. Prime examples of such spectrum are public safety, military and government spectrum, and certain UHF TV spectrum. (2) Several licensed bands such as cellular and PCS bands are highly utilized but utilization varies dramatically over space and time. (3) On the contrary, the unlicensed bands have experienced unfettered network deployment due to low cost technology. In short, spectrum is access limited rather than throughput limited.

Dynamic Spectrum Access (DSA) networks aim to break the spectrum access barrier and enable networks and their end-users to dynamically access spectrum. In this paper, we focus on a specific restricted form of DSA called Coordinated DSA wherein the access to the spectrum in a region is controlled and coordinated by a centralized entity called Spectrum Broker [3]. Unlike the spectrum access models advocated in program such as DARPA XG [1], which require complex spectrum sensing at individual radio nodes and distributed coordination protocols, coordinated DSA relies on regional demand aggregation and centralization of spectrum management decisions.

The spectrum broker forms one of the key control path entities in such networks and design and implementation of scalable versions of such brokers is one of the major challenges. Our paper focuses on algorithms – namely spectrum pricing and spectrum allocation algorithms in the context of design of spectrum brokers for macro-cellular networks. We present our problem formulations and solutions in the context of CDMA networks. However, key concepts are applicable to cellular networks based on other access technologies such as OFDM or TDMA as well.

A. *Outline of the paper*

The rest of the paper is organized as follows: Section II presents background concepts in spectrum management. Section III addresses the problem of spectrum allocation in homogeneous CDMA networks. Section III describes our linear programming formulations to the problem of spectrum management in homogeneous CDMA networks. Section IV describes outline of an algorithm for spectrum allocation in a single region. In Section V, we discuss issues in managing spectrum across multiple regions. Finally, Section VI summarizes our conclusions.

II. CONCEPTS IN COORDINATED SPECTRUM MANAGEMENT

In the following, we describe background concepts in some detail.

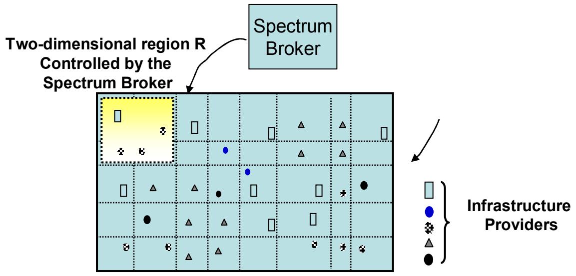


Figure 1: Representative region for spectrum allocation

A. Spectrum management model

In our spectrum management model, for a given region of space ***R,*** a spectrum broker controls the access to a part of spectrum such as *Coordinated Access Band (CAB)* introduced in [1]. The portions of spectrum that are prime candidates to be CAB are Specialized Mobile Radio (SMR) (851-854/806-809 MHz, 861-866/816-821 MHz), public safety bands (764-776, 794-806 MHz), and unused broadcast UHF TV channels (450–470 MHz, 470–512 MHz (channels 14–20), 512–698 MHz (channels 21–51), 698–806 MHz (channels 52–69).

The spectrum broker permanently owns the CAB spectrum and only grants a time bound 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 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. Unlike the current FCC cellular/PCS licenses, which allow the owner long-term multi-year rights to use the spectrum over a large geographic region, broker issued leases are for shorter duration and over a very small region such as a single cell or multiple cells and per transmitter in smallest granularity.

We introduce the notion of a spectrum service provider (SSP) that owns the spectrum broker and therefore, the CAB spectrum. The regulatory authority such as FCC or a separate government owned or private company can run these brokers. One can conceivably have a one-time spectrum auction where multiple entities interested in operating spectrum broker service bid to own CAB.

The region R under broker control can have base stations of several radio infrastructure providers (RIP). The Mobile Virtual Network Operators (MVNOs), also called Network Service Providers (NSP), that offer services such as voice, internet access, telemetry etc. to the end users are customers of these RIPs. Two possible models of spectrum access are possible: (1) in the simplest model, the end-user mobile nodes (MNs) do not participate in spectrum access; only the network elements do. In this mode, the network elements such as Radio Network Controllers (RNCs) that control the base stations may predict the expected end user demands to generate spectrum demands. (2) In a more advanced model, the MNs use a two way control channel to signal their bandwidth requirements to the base stations. Such capability is useful when an end user would benefit from extra bandwidth, for example, when it wants to transfer short burst of large data (files, video). In this case, instantaneous bandwidth demands from users associated with a base station are aggregated by a spectrum estimator to generate total spectrum demand. For example, if ten end users in a base station request 1Mbps each, and a 1.25 MHz CDMA channel can support only 2 such users, up to five such CDMA channels will be required to be configured at the base station. Spectrum estimators are able to relate capacity requests to the required amount spectrum to satisfy these requests. Design of spectrum estimators is technology specific and relies on the knowledge of modulation, RNC scheduling and in-field measurements to create models.

Note that spectrum broker may rely on dynamic characterization of radio interference environment in the region under its control. Such characterization may be feasible via coordinated spectrum sensing by each MN [4] [[1], or via a special sensing network [1] [11] in the data path. Such characterization may be useful to the broker in several ways such as monitoring and enforcement of lease terms, aggressive spectrum reuses for secondary users and smarter spectrum allocation.

B. CDMA Power Control and Spectrum Management

CDMA networks employ power control in both the reverse (MN→Base Station (BS)) and the forward (BS→MN) link for several reasons: (1) *solving the near-far problem*: Without power control, the signal from an MN located near the base station may dominate the signal from a MN far from the base station. (2) *Increase capacity*: CDMA capacity is a function of the interference from other users in the same RF channel; lowering this interference using power control will increase the capacity. In addition, forward link power control, which controls the transmit power of the base station, minimizes interference to other sectors/cells. (3) *Increase battery life at mobile:* Lowering uplink transmit power at the MN will extend battery life

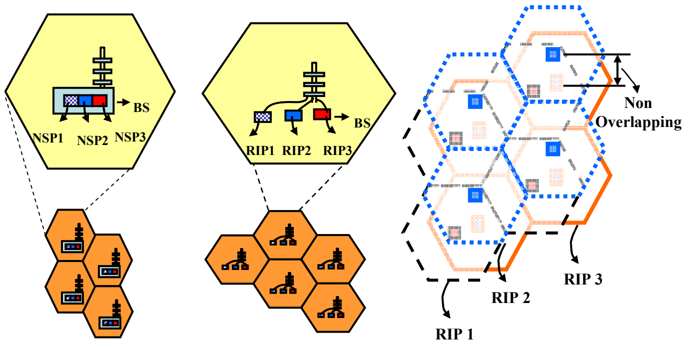
As an example, ANSI-95 systems employ three types of power control: (1) Open Loop Power Control is used to control the MN transmit power during initial system access when there is no power control feedback from the network. Open loop power control provides a coarse initial power setting of the MU during system access. (2) Closed Loop Power Control is used when the connection is established and consists of two components; Inner Loop control that issues rapid 1-bit commands to MN (800 times/sec) to lower or raise MN power to meet a target Signal to Interference (SIR) ratio. The Outer Loop control is used to adjust the target Signal to Interference Ratio (SIR) for the inner loop power control. (3) Forward Link Power Control is used to control transmit power at the base station based on MN reported frame error rates of the forward link.

These complex power control algorithms are typically implemented in the Radio Network Controller (RNC) or Base Station Controller (BSC) that controls several base stations at a time. The frequency reuse of one in CDMA is feasible only in a single infrastructure provider scenario where all BSs and MNs are under the control of a single power control algorithm. The key observation we make is that since each RIP runs its own radio infrastructure, the RNCs and their power control algorithms are independent.

C. Cellular Infrastructure Models

Figure 2 illustrates three relevant infrastructure options:

- **Option (A) Single RIP per region:** In this model, a single RIP owns infrastructure in a region. Its deployed base station serves multiple homogenous (e.g.: all CDMA) or heterogeneous (e.g.: mix of CDMA, TDMA and OFDM) NSPs. One can think of a single BS to consist of multiple logical BSs, one per NSP or even one per end-user or group of users. The advantage of this model is that the broker can maintain a single terrain propagation model for all RIPs. In the context of CDMA providers, this model has several advantages: (1) users of all NSPs are under control of the same power control algorithm in the base station. This allows a carrier frequency and CDMA codes to be shared among different NSPs in the same cells. The co-existence of multiple access technologies in the base station allows more efficient use of spectrum. For example, if there are 10 users in the cell, out of which 6 require ~300 Kbps packet downloads and 4 require regular voice traffic, the RIP can get 1.25 MHz spectrum and operate an EV-DO channel and a single 200 KHz GSM carrier to support remaining voice customers in an 8-slot TDMA system. A homogenous single BS would have either reduced per-user throughput by sharing 1.25 MHz among all users or by allocating two 1.25 MHz channels. In general, shared base station allows spectrum to be used efficiently across different end-user or NSP demands.



(a) Single RIP per region **(b) Colocated Antenna Multiple RIPs** **(c) Non-colocated antenna Multiple RIPS per region**

Figure 2: Cellular Infrastructure options

- **Option (B) Collocated antennas, Multiple RIP base stations**: In this scenario, though the antenna tower is shared, base stations of different RIPs are independent. An example of this scenario is when a town or city requires all wireless providers to use a common tower for their antennas. In the context of CDMA networks, even though a nearly identical radio environment is visible to all providers, only a subset of the user population is visible to a CDMA power control algorithm of each RIP. Assigning same carrier to different RIPs in this case can lead serious loss of throughput as illustrated in Figure 3. Here the power control algorithm for RIP3 would require its end-users that are far from the base station to transmit at high powers. This can seriously interfere with transmissions of user populations of RIP1 and RIP2 which are closer to BS and are therefore instructed to transmit at lower powers. As a result, same carrier frequencies cannot be assigned to the base stations of two different providers when these base stations have overlapping regions of coverage. We call this constraint as cross provider conflict. Even if design changes can be made assigning different pilot, sync, paging and power control channels to different RIPs in the same carrier channel, the cross provider conflict constraint has to be strictly observed in this case.
- **Option (C) non-collocated antennas and non-collocated BS:** This is the most general example where the infrastructure of different providers is deployed independently. Analogous to case above, the cross provider conflict constraints applies to this case as well. However, here it may be possible to relax it under certain circumstances. Specifically, if the BS of two different RIPs are sufficiently apart in radio distance as predicted by terrain propagation models, interference induced by assigning same carrier to different RIPs may be manageable by accounting it as an added small penalty. This may allow more aggressive spectrum reuse across RIPs in a region. One artifact of this model is that it requires each RIP to provide a separate terrain propagation map for its BS placement.

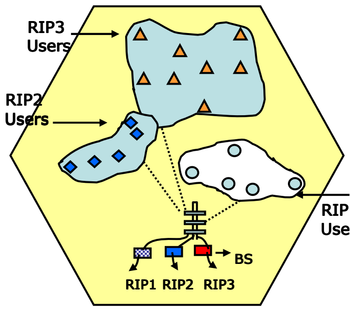


Figure 3: Uncoordinated power control across RIPS

In Option B and C, each RIP may use base stations that only support homogenous access mechanism (CDMA, TDMA, OFDM etc.) or share the BS across different methods.

The three options above deal with macro-cellular networks. Additional cases of micro-cellular networks embedded into macro-cells also need to be considered in spectrum allocation. This case applies especially to in-building or hot spot networks embedded in macro cells. In the context of CDMA networks, mobile nodes in the micro-cells are not visible to the macro-cell power control. If the power levels in the micro-cells are sufficiently low and signal leak out of structures into macro-cell is not significant, same carriers can be reused in micro-cell.

The nature of the infrastructure for which spectrum is being allocated plays a role in the design of spectrum management algorithms for the spectrum broker.

D. Design Considerations in Spectrum Allocation

In the following we account for various considerations in spectrum allocation:

D.1 Spectrum Request processing

The spectrum broker can process spectrum requests it receives in two ways: (1) Online: Each request is processed as it is received and if admitted, it is configured in the appropriate base station (s) independent of future requests. (2) Batched: Requests received in a time window *i* of T units are batched and processed together. The requests that are admitted in the system and allocated are activated in subsequent $(i+1)^{th}$ time window. The batched model has several advantages: (1) it guarantees a fixed, maximum latency for a spectrum demand. (2) It allows correlating and aggregating temporally and spatially clustered requests to optimize spectrum allocation. (3) Allocation and de-allocation of spectrum is done at fixed intervals allowing network and end-user devices to predict transitions and allow higher level protocols to adapt gracefully to possible connectivity disruptions. In our work we focus primarily on batched mode of spectrum allocation.

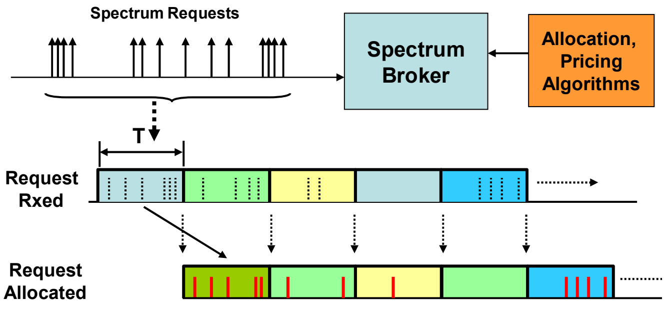


Figure 4: Spectrum allocation model

D.2 Scope of a demand

Typically, a provider request for spectrum is for a particular base station location. However, depending on the kind of multiple access technology used by the provider, interference considerations cause spectrum allocated in one place to impact allocations in neighboring cells. For example, in the case of TDMA networks using a conservative system design, a frequency allocated in a BS cannot be reused in a subset of its neighboring cells to avoid interference. On the contrary, CDMA networks reuse the same carrier frequency in adjacent cells. They exploit multi-path interference constructively and support a soft handoff capability by tracking pilot signal from neighboring base stations. As such, when allocating spectrum dynamically to a CDMA base station, the same assigned carrier frequency must be available in the adjacent base stations as well to support soft handoff capability, especially in a highly mobile environment. We capture these considerations in a parameter called **scope** defined as a 2-tuple (x, y) describing how many adjacent base stations should be taken into consideration when allocating spectrum. In the case of GSM networks, **scope** defines a region over which same frequency cannot be used where as in CDMA networks it captures region over which same frequency must be reused.

D.3 Demand Stickiness and Access Fairness

In the batched model, the simplest allocation model leases spectrum only for the time duration of *T* units. However, if *T* is small, this can lead to frequent spectrum demands and significant disruption in the network service to end-user devices. As such a provider should be allowed to request the desired duration of a demand be multiples of *T* units; the larger the multiple, the better the service continuity. The concept of *stickiness* captures this; it is defined as the number of consecutive time slots an accepted demand can continue to use its spectrum allocation.

Access fairness is the other side of the coin of *stickiness.* In case of high demand situation, if an allocated demand *sticks* in the system for long, it hogs the capacity and denies other provider demands an opportunity to access spectrum. So access fairness demands that under heavy load, no single provider gets prolonged access to spectrum unless they pay a proportionately higher price. There are two kinds of stickiness we envisage:

- **Deterministic sticky:** A demand is guaranteed to be sticky for the requested number of timeslots N. This is a form of an advanced reservation.
- **Probabilistic sticky:** The continuation of a demand in a future time slot is probabilistic. In the simplest case, the spectrum broker can perform a coin toss to decide if the demand is reconsidered for the allocations to be configured in the next time slot. A better method is to make the stickiness probability a function of the number of consecutive slots already used, the maximum number of slots requested and the service provider as well as the system utilization in last (n-1) slots. An example function could be as follows:

Eqn 1:

$$\text{Pr(Demand sticks in slot n)} = \frac{\left[f(S_{u,}D_u(n-1,n-2,..1)\right]}{(\text{n-1})^{\alpha}.N^{\beta}}$$

In this example, as demand is satisfied for more consecutive slots, its probability of continuing in the system drops as a function of maximum number of slots N and number of slots allocated up to the current time. Also, if the demand has already been satisfied for (n-1) slots and has experienced significant utilization, it desirable to continue to satisfy it. Therefore, the numerator of Eqn 1 is an increasing function of system and demand specific utilization. The *stickiness probability* is also called the *favorability rating.*

Fairness has been extensively studied in resource sharing frameworks, especially, sharing of a communication link and networks by packet flows. Among various fairness criteria possible, we advocate use of classic *max-min fairness.* This criterion attempts to maximize the allocation of the demand receiving the poorest allocation. The weighted max-min fairness with favorability ratings as the weights is the framework we use in our work.

D.4 Utilization of Allocated Spectrum

It is critical that in a DSA network, if a provider is awarded spectrum, it demonstrates use of that spectrum above a certain threshold. This is necessary to ensure that big providers do not use financial power to buy out spectrum from the broker and leave it vacant to starve smaller size competition. Therefore, spectrum allocation must require providers to furnish information on their past spectrum utilizations for future demands.

D.5 Demand Model

Each spectrum demand is an n-tuple with parameters such as: (1) Location of the BS at which the demand will be configured, (2) amount of spectrum required specified as a range [d_{min},d_{max}], (3) time duration for which the spectrum will be used, also called the sticky length., (4) identity of the network provider, (5) optional price bid, (6) spectrum utilization history, and (7) demand scope, that is the spatial region over which request will be instantiated.

Our model above requires that at least d_{min} amount and at the most d_{max} amount of spectrum be allocated to a RIP. The minimum guarantee helps the RIP provide service continuity and meet demand surges. An alternate "all-or-nothing" demand model where RIP requests only d_{min} channels is also possible.

Our spectrum management algorithms assume the above demand models.

E. Spectrum Pricing

The spectrum pricing can work in three modes as detailed below:

- **Merchant mode:** The system determines the spectrum price based upon current utilization and demand. The price is then advertised on a "take-it or leave-it" basis and is assigned on a first come basis. No negotiation is conducted with the spectrum user. This model is appropriate when the demand is less than the available spectrum.
- **Simple bidding:** In this mode, the network again determines the initial spectrum price. However, the spectrum consumer is allowed to describe in a demand request a price bid it is willing pay. The broker collects all such bids for all locations in the entire region. In the case where the demands exceed available spectrum, machine driven auctions are conducted to decide bid-winners. In this single step bidding model, a winning bid is binding for the requestor. The broker may use combinatorial auctions
- **Iterative bidding:** In the *simple single step bidding* scenario, it is possible we may encounter cases where spectrum allocation fails for a winning bid. In this case, the bidding process may have to be iterated again to take into account this conflict in spectrum allocation. In addition, if a spectrum demand can be only partially satisfied, the broker may allow the consumer to negotiate if it wants to take partial resource or release its requests. In either case, the broker may do another iteration of bidding by reconsidering bids that lost in the earlier round. Iterative bidding requires an involved protocol and a bidding scheme with convergence guarantees and tight time constraints.

F. Basics of Spectrum Allocation

The cellular networks with DSA may use any of the multitude of available technologies such as CDMA2000 (1xRTT, 1xEV-DO, 1xEV-DV) [7], IMT-2000 (UMTS, GSM/GPRS/EDGE) [6], and WiMAX [8]. Each of these technologies differs in their spectrum requirements. As such, the spectrum allocation problem presents a range of complexity (Figure 5). On this range, from left to right the complexity of the spectrum allocation problem increases as we deal with heterogeneous networks. On the very left, we have spectrum allocation for homogeneous networks – such as CDMA networks based only on 1xRTT which require carrier frequencies with B_1 =1.23 MHz spectrum[1]. Within this class, CDMA 3xRTT, requires B_2 = 3.75MHz spectrum per carrier, whereas UMTS networks require 5 MHz spectrum. At the next level of complexity, spectrum allocation has to deal with demands from a mix of providers of these networks. Putting TDMA and OFDM based networks in the mix increases the allocation complexity further.

In the most general mode of allocation, the entire CAB band may be freely shared, requiring a very complex algorithm. Instead we suggest a simpler formulation (), where the CAB is split into multiple bands assigned to each class of networks such as CAB for CDMA, OFDM, and TDMA. The boundary between adjacent multiple CAB bands is not a priori fixed and can vary to respond to demand characteristics.

Additional details of our model are as follows:

- The broker controls a contiguous band of B MHz spectrum that is divided into ***N*** contiguous channels each ***C*** MHz and ***N=(B/C)***.

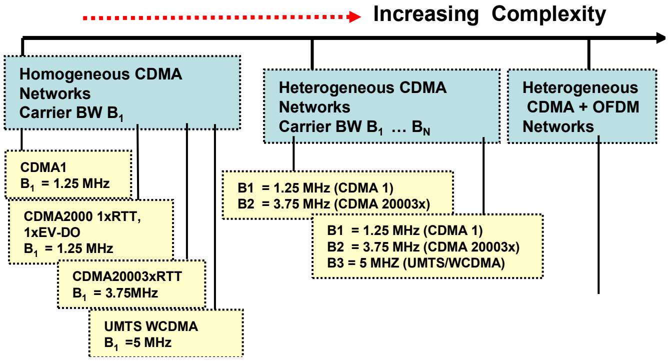


Figure 5: Range of spectrum allocation problems

- ***M*** RIPs operate their base station in the region. Each RIP entity registers it exact location BS(x_i, y_i) and capabilities of the radio hardware such as the number K_i of radio Transmit Receiver (TRX) (radio interface) units, maximum power $P_{max}(i)$, minimum and maximum frequency band per TRX.
- The broker has a-priori knowledge of the terrain under control and empirical radio propagation models for the frequencies under consideration [9]. This model enables the broker to estimate, for a given transmit power at a point (x_i, y_i), received power at all other points in the terrain. Using such information the broker can estimate the extent of interference and regions of interference between TRXs in the region.

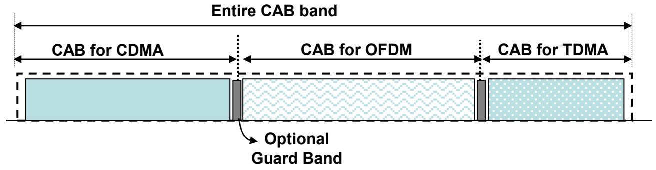


Figure 6: Simpler allocation model

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[1] 1.23 MHZ with a separation between center frequencies of 1.25 MHZ

In the following, we consider the problem of spectrum management for homogenous CDMA networks.

III. SPECTRUM ALLOCATION FOR HOMOGENOUS CDMA NETWORKS IN A SINGLE REGION

When assigning channels to the various TRXs in the BS in a region, the following constraints must be met: (1) *co-cell separation:* Same channel cannot be assigned to two different TRX in the same BS. (2) *Collocated cross-provider conflict:* Two collocated base stations corresponding to two different RIPs that share antenna infrastructure cannot be assigned same carriers. This constraint cannot be violated. (3) *Remote cross-provider conflict:* Same channel cannot be assigned to two different TRX in two remote BS corresponding to different providers if they are within interference range of each other. This constraint can be violated only if the interference is limited to be below a limit I_{max}. (3) *Soft-handoff constraint:* Given a BS of a provider, same channel should be preferably assigned to all the base stations in the (neighbor) scope of BS.

We introduce the concept of ***conflict graph*** that captures these constraints. The conflict graph has similarities to the interference graph used in frequency assignment for GSM networks. In fact, a lot of our work derives and enhances from the formulations for these problems [2] [4].

In the simplest form of a conflict graph, we represent each base station by a single node or vertex v in the graph $G = (V,E), |V| = n,. |E| = m$. Two nodes v, w have a edge $e = (v, w)$ between them, if they belong to two different providers and cannot be assigned same channel. This representation captures the cases when the BS of different providers are collocated or physically separated. Figure 7 illustrates a simple example of a conflict graph for ten BS corresponding to three different RIPs. Note that nodes 1, 8, 10 correspond to same provider and do not have conflict edges between them, whereas 1, 2, 3 belong to different providers and therefore have conflict edges. Node 9 and 1 do not have a conflict edge even though they belong to different RIPs as they are not in the interference range as predicted by the terrain propagation model for the frequency range under consideration.

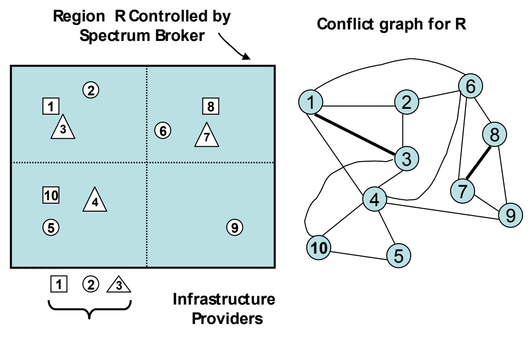

Figure 7: Simple example of conflict graph

We define $m(v)$ as the total number of channels assigned to the base station corresponding to node v. If we define,

$$x_{vf} = \begin{cases} 1 & \text{if } f \in F(v) \\ 0 & \text{otherwise} \end{cases}$$

where $F(v)$ is the set of available channels at v, then

$$\sum_{f \in F(v)} x_{vf} = m(v) \ \forall \mathrm{v} \in V .$$

If vertex v *is* assigned channel f and vertex w is assigned channel g, and an edge vw exists, then $|f\text{-}g|$ is called distance between two nodes. Associated with every edge vw, is a set T_{vw} which contains all forbidden distances, such that for all $d \in T_{vw} = \{0,1,....d(vw)-1\}$, $|\text{f-g}| \geq \text{d}$. Clearly, the constraints above cannot be violated in a channel assignment and therefore are called *hard constraints.* Such constraints capture the case of co-located BSs of different RIPs sharing the same antenna infrastructure (Figure 2, Option (B)). In Figure 7, they apply to edges 1-3, 7-8 and 5-10 that capture collocated cross-provider conflict. If they are used to model case in ((Figure 2, Option (c)) as well, they may often render channel assignment infeasible. Hence, we introduce soft constraints [4] which can be violated if required. For a pair of nodes v, w, a soft constraint is defined in the form of a penalty function $p_{vw}(f,g) = F_v \times F_w \to \mathbb{R}_+$ which captures interference levels when frequencies f, g are assigned to v, w. In case of CDMA networks, p_{vw} is defined as follows

$$p_{vw}(f,g) = \begin{cases} c^{co}(vw,f) & \text{if } f = g \\ \ell(\text{f,g}) & \text{otherwise} \end{cases} \text{.........(1)}$$

The terrain propagation models are used in predicting $p_{vw}(f)$. These capture the remote cross-provider conflict.

An alternate representation of conflict graph is also feasible where each TRX at a base station is represented by a single vertex. So if BS_i has K_i TRX units, it is represented by K_i nodes. The *co-cell separation* constraint dictates that in the conflict graph there is an edge between all K_i interfaces. Clearly, the conflict graph in this representation can be quite large.

Also, note that for each conflict graph vertex v, there is an associated set $scope_{pq}(v)$ such that any vertex $w \in scope(v)$

We consider three different formulations derived from various formulations in [2][4].

A. Feasibility DSA (F-DSA)

The Feasibility-DSA (F-DSA) is a formulation that meets following criteria

$$\sum_{f \in F(v)} x_{vf} = m(v) = demand \ \text{d} \quad \forall v \in V \quad (1)$$

$$x_{vf} + x_{wg} \leq 1 \quad \forall (v,w) \in E, f \in F(v), g \in F(w)$$
$$p_{vw}(f,g) \geq p_{\max} \qquad (2)$$

$$x_{vf} + x_{wg} \leq 1 \quad \forall (v,w) \in E, f \in F(v), g \in F(w)$$
$$|f - g| \in T_{vw} \qquad (3)$$

The first constraint requires that the total number of channels assigned to v add up to the demand d. The second constraint (2) requires that if two nodes v, w are assigned frequencies f, g, then the penalty must be less than the maximum tolerable threshold p_{max}. It accounts for the cross-provider conflict soft constraint. The third criteria accounts for the hard constraint for cross-provider conflict. Here T_{vw} represents the set of blocked distance for edge e=(v,w). The set T_{vw} can also be computed using the criteria that $p_{vw}(f,g)$ not exceed p_{max} for a given f,g.

This formulation does not optimize any criteria and also, does not account for scope constraint desirable in CDMA systems. A solution satisfying these criteria is called *Feasibility Solution*. Often times, a feasibility solution may not exist and therefore, alternate formulations that attempt optimize a criteria are desirable. We consider two formulations: (1) Maximizing number of assigned frequencies that meet required demands, (2) Minimizing total interference in the region.

B. Maximum Service DSA (MaxServ-DSA)

Let us define a binary variable z_{vwf}

Eqn 2

$$z_{vwf} = \begin{cases} 1 & \text{if } x_{vf} = x_{wf} = 1 \\ 0 & \text{otherwise} \end{cases}$$

$$\alpha(v) = \left(\sum_{w \in scope(v)} z_{vwf} \right) \leq \ | scope(v) |$$

Note that z_{vwf} captures the case when vertex v and its neighbor both are assigned channel f. The term $\alpha(v)$ defined as the sum of z_{vwf} over the *scope(v),* captures how well the soft-handoff constraint is met over the scope. Note that for each vertex *v, scope(v)* is a-priori defined based on received demands.

Let *n(v)* be the number of channels assigned to vertex in response to demand [d_{min}, d_{max}]. Then, our overall objectives are: (1) meet demands of maximum number of vertices (i.e. RIPS BSs) and (2) also, meet the soft handoff constraint of maximum vertices. We tabulate the following integer program **IP1** which characterizes the *MaxServ-DSA* formulation.

IP1:

Eqn 3

$$\max \sum_{v \in V} \big(w.n(v) + (1-w).\alpha(v) \big) \qquad (1)$$

st.

$$n(v) \leq d_{\max}(v) \qquad (2)$$

$$d_{\min} \leq n(v) \qquad (3)$$

$$n(v) = \sum_{f \in F(v)} x_{vf} \qquad (4)$$

$$x_{vf} + x_{wg} \leq 1 \quad v, w \in V, f \in F(v), w \in F(w)$$
$$p_{vw}(f,g) \geq p_{\max} \qquad (5)$$

$$x_{vf} + x_{wf} \leq 1 + z_{vwf} \quad \forall v, w \text{ s.t. } w \in scope(v) \quad (6)$$

$$z_{vwf} \leq x_{vf}, x_{wf} \qquad \forall v, w \text{ s.t. } w \in scope(v) \quad (7)$$

The objective function in Eqn 3.1 uses a weighting factor *w* to indicate relative importance of two criteria. The constraints in Eqn 3.2 and Eqn 3.3 capture the requirement that *n(v)* must meet the demand criteria. The constraint Eqn 3.5 captures the cross-provider conflict constraint much the same way as F-DSA formulation. We can simplify this constraint by using the T_{vw} = {0} formulation, which would account only for co-channel interference. We add constraints Eqn 3.6 and Eqn 3.7 to ensure that z_{vwf} obtains the right values as specified in Eqn 2.

C. Minimum Penalty DSA (MinP-DSA)

In this formulation the objective is to minimize the sum of penalties p_{vwfg} incurred by all frequency assignments. We consider two kinds of interference for CDMA case: (1) same channel is assigned to BS of same RIP and (2) same channel is assigned to BS of different RIPs with a certain penalty. The total co-channel interference in the region for case (2) above can be written down as follows:

Eqn 4

$$\sum_{(v,w) \in E} \sum_{\substack{f \in F(v), \\ f \in F(w)}} p_{vwfg} x_{vf} x_{wf}$$

The most general penalty constraint can be characterized as

Eqn 5

$$\sum_{(v,w) \in E} \sum_{\substack{f \in F(v), g \in F(w) \\ |f-g| \in T_{vw}}} p_{vwfg} x_{vf} x_{wg}$$

The interference for case (1) above is written down as

Eqn 6

$$\sum_{v \in V} \sum_{w \in scope(v)} p_{vwf} x_{vf} x_{wf}$$

Clearly, in case of CDMA, case 1 above can be handled by power control mechanisms and as such explicit reduction of that may not be necessary. Therefore our objective is to minimize the difference (Eqn 4 - Eqn 6). However, since the terms $x_{vf} x_{wf}$ are quadratic in terms, we define

$$y_{vwf} = \begin{cases} 1 & \text{if } x_{vf} = x_{wf} = 1 \\ & 0 \text{ otherwise} \end{cases}$$

Eqn 7

$$\min \left(\left(\begin{array}{l} \displaystyle\sum_{(v,w) \in E} \sum_{\substack{f \in F(v), g \in F(w) \\ |f-g| \in T_{vw}}} p_{vwfg} . z_{vwfg} \\ \displaystyle -\sum_{v \in V} \sum_{w \in scope(v)} p_{vwf} y_{vwf} \end{array} \right) \right) \qquad (1)$$

s.t.

$$\sum_{f \in F(v)} x_{vf} = d(v) \quad \forall v \in V \qquad (2)$$

$$x_{vf} + x_{wf} \leq 1 + y_{vwf} \quad \text{for } v \in V, \ w \in scope(v)$$
$$f \in F(v), F(w) \qquad (3)$$

$$x_{vf} + x_{wg} \leq 1 + z_{vwfg} \quad \text{for } (v,w) \in E, f \in F(v),$$
$$g \in F(w), | f - g | \in T_{vw} \qquad (4)$$

In this formulation, per vertex demand is specified as a single quantity instead of a range (Eqn 7.2). The constraint Eqn 7.4 captures penalties for forbidden distances and co-channel allocations, whereas constrain Eqn 7.3 captures the scope constraint.

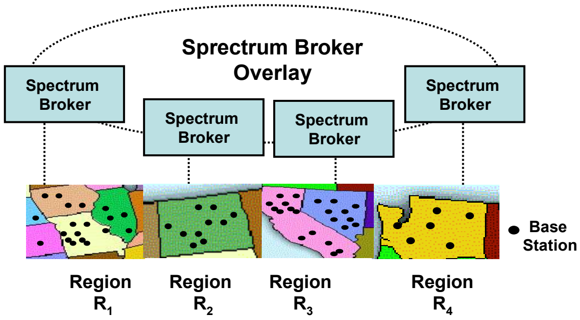

Figure 8: Spectrum overlay for multiple regions

Both MinP-DSA and MaxServ-DSA are NP-complete or harder. Currently, we are exploring using standard Branch-and-Bound techniques for obtaining exact solutions for reasonably large networks. One of the problems in simulating these solutions is that no good benchmark topologies are available. We plan to seek realistic topologies of cellular networks from different vendors and generate coordinated DSA topologies by superimposing them.

IV. Spectrum Broker For SINGLE Region

For each BS, the broker maintains a *Spectrum Allocation Map (SAM)* data structure which records what part of CAB spectrum is allocated and *Free Spectrum Map (FSM)* that records available parts of CAB band.

$$D_{new}(n) = \left\{ \begin{matrix} \text{Set of all demands received by} \\ \text{the spectrum broker during time slot } n \end{matrix} \right\}$$

$$D_{expire}(n) = \left\{ \begin{matrix} \text{Set of all demands expiring at the} \\ \text{end of slot } n \end{matrix} \right\}$$

The spectrum allocation and pricing can be performed to optimize one or more of the following objectives: (1) Maximize revenue in the region in each slot or over a time horizon. (2) Maximize spectrum utilization over the region. A blind revenue optimization scheme may favor providers who can pay more to outbid others and “hog spectrum”. As such it is agnostic to fairness considerations. Our stickiness framework assigns “favorability ratings” to “sticky demands” which account for (1) time spent in the system and (2) utilization of configured capacity in the previous slots. Given this, we can compute

$$D_{sticky}(n) = \left\{ \begin{matrix} \text{Set of demands that successfully pass the} \\ \text{stickiness criteria at the end of slot } n \end{matrix} \right\}$$

$$\begin{aligned} D_{cand}(n+1) &= \{\text{Candidate demand set for slot } (n+1)\} \\ &= ([D_{new}(n) \cup D_{sticky}(n)]) \end{aligned}$$

Using the $D_{cand}(n+1)$ set, we generate a demand set at each base station location BS, $D_{BS}(x_i, y_{i,}, n+1)$. Note that non-zero *scope* requirement of some of the demands generates additional demands at adjacent base stations. Using $D_{expired}(n)$ and $D_{sticky}(n)$, we can update SAM(x_i , y_i , n+1), *FSM*(x_i , y_i , n+1).

The broker then uses one of the MinP-DSA or MaxServ-DSA formulations above and an efficient exact solution or heuristic based method to obtain the possible solution. If $n(v)$ at all nodes meets the $d_{\min} \le n(v) \le d_{\max}$ condition, the allocation has met each RIP’s demands. Otherwise, the broker sets d_{max} of the largest demands for nodes with small favorability ratings to their $d_{min}+1$ values and attempts to obtain a allocation where for all *v*, *n(v)* criteria is satisfied as $d_{\min} \le n(v)$. The algorithm thus attempts to aggressively meet the d_{min} demands first and then strives to meet d_{max} as much as it can. This is analogous to the min-max fairness definitions. In our ongoing work, we are attempting to formalize these notions.

V. Spectrum Allocation Across Multiple Regions

The regional approach to spectrum management results in many smaller geographic areas each associated with its own spectrum broker (Figure 8).

If non-overlapping parts of dynamically sharable spectrum are used in adjacent regions, spectrum in each region can be managed independently. On the contrary if the same spectrum band is accessed in all regions, spectrum allocation in areas of each region which border neighboring regions needs special consideration. If the spectrum brokers for two regions which share borders do not coordinate, then reuse of same channels can result in poor performance in these border areas. Note that for each region we need to consider its 8-neighborhood region.

There are two possible solutions to eliminating these conflict scenarios: (1) The simplest approach relies on dividing the spectrum band into eight sub-bands and a-priori restricting a sub-band as “blocked” frequencies in the areas of overlap. Such static allocation, while it works, is contrast to spirit of DSA; it renders 7/8th of the spectrum band inaccessible in the overlap regions. The advantage however is that each broker a-priori decides and publishes its “unused” sub-bands to all its peering brokers which can use them in the overlaps. In the case of a simple grid subdivision a large region and a single broker per sub-region, maximum two bands per square region are sufficient. (2) In this case, no bands are statically blocked; instead each broker publishes its allocations or its “forbidden list of channels” to its neighbor every cycle of allocation. Other peering brokers attempt to respect the “blocked list” in their allocation. This mechanism requires time synchronization of brokers and incorporation of “blocked list” in the dynamic allocation at each broker. Also, in the worst case, the conflict resolution phase can have cascading effect across the entire region which may make allocation latency hard to bind.

One simple, yet practical solution in the context of CDMA networks is to completely eliminate possibility of conflict in “border areas”. In our case, if base stations of two or more RIPs exist in the border areas, conflict is possible. If we mandate that only one RIP provides coverage in the border areas, then reallocating the same frequency across the region boundaries results in soft-handoff, whereas allocating different frequencies results in hard handoff. In both cases, no spectrum is lost for dynamic access. This however is similar to static allocation. Alternatively, if multiple RIPs operate in the border areas, only one of the RIP is allowed to activate spectrum in the conflict region at any given instance. This improves access efficiency for different RIPs.

VI. CONCLUSIONS AND ONGOING WORK

In this paper, we addressed spectrum management for new kind of cellular networks that employ coordinated spectrum access.. We outlined key concepts in spectrum management, namely spectrum management and allocation models, various infrastructure options, and other key concepts such as demand scope, access fairness and stickiness. We presented two linear programming formulations: MaxService-DSA and MinPenalty-DSA for solving the spectrum allocation problem. We briefly identified issues in spectrum allocation across multiple regions.

. In our ongoing work, we are focusing on three directions: (1) formulating spectrum pricing problem as a combinatorial auction. (2) Refining max-min access fairness framework for use in a spectrum broker and (3) implementing the allocation and pricing framework in a simulator to study its performance for various network topologies and demands models.

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