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Dynamic Spectrum Management in Cellular Network

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***Abstract*- In 1934 the US Congress created the Federal Communications Commission (FCC) to consolidate the regulation of interstate telecommunication and supersede the existing Federal Radio Commission. Among its responsibilities is the management and licensing of electromagnetic spectrum within the United States and its possessions. For example, it licenses very-high frequency (VHF) and ultra-high frequency (UHF) broadcast television (TV) stations and enforces requirements on infestation interference.**

The 21st century has seen an explosion in personal wireless devices. From mobile phones to wireless local area networks (WLAN), people want to be perpetually networked no matter where they are. Services like mobile phone and global Positioning system (GPS) use frequencies licensed by the FCC, while others like WLAN and Bluetooth use unlicensed bands. The most popular unlicensed bands are the Industrial, Scientist, and Medical (ISM) bands at 900 MHz, 2.4 GHz, and 5.8 GHz. While setting up a home wireless network to access your broadband Internet connection does not fall within the original \ISM" dentition, lack of general use of these bands prompted the FCC to loosen restrictions. Within these frequency ranges, anyone can transmit at any time, as long as their power does not exceed the band's regulatory maximum. The end result is that the ISM bands are crowded. We now have cordless phones interfering with home audio networks interfering with the uplink from your personal digital assistant (PDA) to your computer.

Dynamic spectrum management involves the identification and characterization of available spectrum, allocation of this spectrum to one or more users/services, the usage and monitoring of the allocated spectrum and release of this allocated spectrum as each user/service completes their individual information-transfer tasks. The key objective of Dynamic spectrum management (DSM) however is the facilitation of interference-free co-existence of services/entities on a common (or multiple) spectrum segments.

***Index Terms*— Spectrum management, Cellular system, Channel allocation, Dynamic Spectrum Access**

I. INTRODUCTION

Static allocation offers negligible channel acquisition time and zero message complexity and works well at a low system load; the performance steadily decreases as system load increases since many calls are dropped; in case of even temporary hot spots many calls may be dropped by a heavily loaded switching station even when there are enough idle channels in the interference region of that station. On the other hand, dynamic schemes provide better utilization of the channels at higher loads albeit at the cost of higher channel acquisition time and some additional control messages. Our purpose in the present paper is to propose a distributed dynamic channel allocation scheme that each switching station can tune to its own load independent of other stations in its interference region; the objective is to minimize the call block/drop rate and at the same time maintain a minimum average channel acquisition time and minimum control message complexity and maximum bandwidth utilization.

Mobile computing has found increased applications and gained importance in recent years. Managing radio resources in cellular systems has always been a very important aspect of system design, due to limited availability of resources. In channelized cellular systems, the radio resource under consideration is a channel, which can be defined as a time slot, a carrier frequency or a combination of both. In such a network, the geographical area is divided into hexagonal cells. The mobile telephones in each cell are serviced by a base station located at the center of the cell and base stations are connected via a wired network. The available wireless bandwidth is divided into channels, where each channel is capable of supporting a communication session. If a particular channel is used concurrently by more than one call originating in a cell or in neighboring cells, the call will interfere with each other such interference is called co-channel interference. A channel can be used simultaneously in different cells without unacceptable interference provided the distance between each pair of cells is greater than or equal to minimum reuse distance. This is known as frequency reuse. The problem of channel allocation is to allocate channels to cells so that the available bandwidth is utilized most effectively by the various cells to meet the traffic demand in each cell without interference with the neighboring cells.

A National Spectrum Goals

The Communications Act of 1934 provides, in Section 151, guidance regarding spectrum management objectives. It states that the FCC is to regulate: so as to make available a rapid, efficient, Nation-wide, and world-wide wire and radio communication service with adequate facilities at reasonable charges, for the purpose of the national defense, [and] for the purpose of promoting safety of life and property. Title III of the Act authorizes the FCC to regulate generally the "channels of radio transmission," including the licensing and operation of radio stations, but provides few details on the FCC's objectives for spectrum management. The Act empowers the FCC to act consistently with the "public interest, convenience, or necessity." The "public interest" standard is the primary criterion for apportioning non-federal spectrum in the United States, although the Act mentions the goals of preventing interference among stations, promoting the efficient use of spectrum, and promoting public safety. The Act does not define the "public interest," but instead gives the FCC broad discretion to elucidate and give specific content to the public interest standard. NTIA has identified spectrum management objectives to guide Federal users of the radio spectrum. These objectives are similar in intent to the Act's guidelines and state that the Federal agencies are to "make effective, efficient, and prudent use of the radio spectrum in the best interest of the Nation, with care to conserve it for uses where other means of communication are not available or feasible." NTIA interprets the standard "effective, efficient, and prudent," and the reference to "the best interests of the Nation" as encompassing the overall benefits the American public derives from radio communication services, both Federal and non-federal, as well as the needs of various Federal users and choices among competing users[3].

II. SYSTEM MODEL

We assume cellular communication system that divides the geographical region served by it into hexagonal cells, with a base station in the center of each cell. A base station can be in wireless communication with the mobile unit in its cell. Calls involving mobile computers will be collectively referred to as communication session. All the cells except that at the boundaries have 6 neighbors.

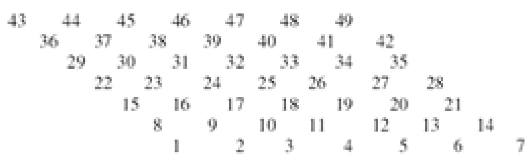

Fig.1. 7x7 Grid Cellular System

The system has been assigned a frequency band that is divided into a finite number of wireless channels. These channels are independent of each other so adjacent channel interference can be neglected. However, a channel should not be concurrently be used in more than one communication session in the same or neighboring cell. However, the channel may be used exclusively for the control message sent during link setup between mobile host and base station of the cell. Remaining channels are used to support calls. A mobile host can communicate with other units, mobile or static, only through the base station of the cell in which it is present. A mobile unit initiates a call when it wants to communicate with other or call arrives from other user. If the connection request can be satisfied channel is allocated for the call.

A. Overview of Static Spectrum Allocation

According to the concept of GSM technology each base station is allocated by fixed frequency band by using the concept of frequency reuse. We can extend our network as large as possible by using this frequency reuse concept. In such static technology each base station uses 5% of their total frequency band [4] as a control channels and remaining 95% as a traffic channels. Specifically these 5% control channels are used for managing overall communication such as call setup, call termination, call processing and other related functions. Traffic channels purposely used for sending information that wants to send from one point to other.

B. Spectrum Management Process

Management of spectrum is the combination of administrative and technical procedures with legal connotations necessary to ensure efficient operation of radio communication services without causing harmful interference. Efficient and effective Spectrum management, therefore, needs to be the garden signs of carefully planning spectrum allocation in a co-ordinate manner without compromising national interests and efficiently assigning frequencies for the benefit of users at large with minimum scope of harmful interference. There are forty different kinds of radio communication services, including safety services like aeronautical, maritime, radio navigation, radiolocation, radio astronomy, meteorological, broadcasting, satellite broadcasting, fixed, fixed-satellite, mobile, mobile-satellite, space services, etc. In accordance with international treaties, all the frequency bands are shared amongst different types of radio communication services for variety of applications and technologies by different countries. The basic tools of radio frequency sharing require application of principles of time sharing, technical sharing and geographical sharing. No user can work in isolation, no service can work in isolation and no country can work in isolation. It is a collective Spectrum management exercise and radio regulatory mechanism which alone can ensure the interference free operation of various networks. It is the individual frequency, which is assigned to a user or a service provider and not a frequency band. No wireless user or service provider, be it a government of private, has ownership claim on any part of the frequency band, only frequency assignments [2] are made in a particular frequency band, as per national and international plans and regulations, for operation of radio networks owned by an agency.

National and international coordination, sharing, coexistence and protection are key elements of Spectrum management process. National and international aspects of radio regulatory process are completely interlinked. Radio regulatory process has multifarious activities, which include, among others, interaction with International Telecommunication Union (ITU), with administrations of other countries, national and international frequency planning and coordination, formulation of legislation, tools and regulations, implementation of national and international rules, formulation of channeling plans, etc. Electromagnetic compatibility (EMC) is consensus solution for efficient and economically utilization of radio frequency spectrum. Society’s increasing use of radio based technologies for various telecommunication applications, and the tremendous opportunities provided by these technologies for socio-economic development, highlight importance of the electromagnetic compatibility among various radio communication systems. Advances in technology have made it practicable to implement new sharing schemes that offer possibilities for increasing the efficiency of Spectrum sharing and frequency utilization.

C. Making Spectrum Pooling Work

The full potential of spectrum pooling will be realized when enabled among multiple classes of spectrum holders (public safety, commercial, federal and business/industrial licensees) using multiple spectrum bands. While political, economic, regulatory and organizational barriers may preclude the emergence of such generalized sharing for a long time, there are still significant benefits to be had from pooling spectrum more narrowly, among subsets of licenses and licensees. The public safety community and its dedicated spectrum present just such an opportunity. In fact, the necessity for spectrum sharing has already been identified between federal, state and local spectrum holders to accomplish broadband networking, as a result of the WARN experimental network in the DC area33 and the Alaska Land Mobile Radio (ALMR) system.34 Spectrum sharing is also a key underpinning of the proposed national shared broadband wireless network (SBWN) contemplated for the D-Block 700 MHz spectrum combined with the public safety 700 MHz block.35 While the public safety community has recognized the need for more spectrum sharing, the mechanism for sharing has not been adequately addressed. To fully realize the benefits of sharing on a large, national scale standardized approaches toward sharing need to be developed. Such standardized approaches will simplify negotiating multilateral sharing agreements and will facilitate the design and production of equipment that can take advantage of pooled bands.

III. PROBLEM DESCRIPTION AND THEIR RELATIONSHIP

A. Mutual Exclusion

Earlier a scheme was proposed in which each cell maintains channel occupancy matrix information about which channels are currently in use by the cell in question as well as by the neighboring cells. When a new call needs to be serviced by the current cell it identifies a free channel by consulting the occupancy matrix and assigns it to that call. The problem arises if the neighboring cell also allocates the same channel at the same time to service one of its calls. This leads to interference among cells. This problem can be viewed as a problem of resource sharing. Thus, neighboring cells should access the resource in a mutually exclusive manner. But in distributed dynamic channel allocation the same channel can be used simultaneously by several cells and is not allowed by two cells within the minimum reuse distance of each other. Also instead of dealing with a single resource we are dealing with multiple channels. One class of solving the mutual exclusion problem is the token-based algorithm, which is not suitable from cellular system as a number of cells can use the same channel. The other class of algorithm is non-token based. A common idea is that the various processes exchange information with each other about which process is currently using the resource and which processes are waiting to access the resource. Thus an information structure which consist of a number of sets in which appropriate information about the current state of system is stored needs to be developed.

B. Channel Allocation

A cellular network is a regular grid of hexagonal cells. An n*m cellular network has n rows and m columns of cells. The cell at row i and column j are denoted as (i, j) .the distance between two cells c1 (i1, j1) and c2 (i2, j2) is calculated as

$$Dist(c1,c2) = (i1-i2)2 + (i1-i2)(j1-j2) + (j1-j2)2$$

A number Dmin, the minimum reuse distance is specified. A channel can be used simultaneously by a number of different cells only if the distance between each pair of cells using the channel is greater than or equal to the minimum reuse distance. Thus, each cell c is associated with an interference neighborhood INc that is a set of cells whose distance to c is smaller than Dmin

$$INc = (ci : dist(c,ci)\langle D\min)$$

If a channel is being used by cell c, then any cell in INc cannot use it.

C. Relaxed Mutual Exclusion

A system consists of a set of sites S= (S1, S2, ÖÖ. Sn) where n is number of cells and a set of critical resources CR= (R1, R2, Ö.., Rm) where m is number of channels .critical resource may be shared according to the following rules of relaxed mutual exclusion-

1. A given critical resource may be used simultaneously at different sites as long as no two of them are mutually interfering.
2. At any single site, two or more processes may not share a given critical resource. Our data structure for relaxed mutual exclusion consist of two sets

1. Ri: site i must acquire permission from all the sites in Ri before acquiring the Channel.
2. Ii: site i must inform all the sites in Ii when it releases the Channel.

D. Solving or Avoiding Deadlocks

A deadlock occurs when both the sites are waiting for grant message. The effective way to avoid deadlock is by the use of reject message. After a site receives a request, it either grants or rejects the request within a limited amount of time if the request is rejected then it generate a request for other channel.

E. Dealing with Multiple Channels

In cellular system CR= (R1, R2... Rm) i.e. there a m number of channels available instead of one. Thus, we need to search a free channel from the m available channels when a call needs to acquire a channel. The techniques available for channel searching are

1. Sequential search: When a cell wishes to acquire a channel, it selects a channel r e CR. Test whether r is a free channel using algorithm (r). If request for r fails, try other channel r× and repeat the process until a free channel is available.
2. Parallel search: When a cell wants to acquire one or more channel it executes algorithm(c) for all c (all available channels) simultaneously to determine whether it can acquire channel c.
3. Hybrid search: This is a combination of sequential and parallel search [4].

IV. OPTIMIZATION METHOD

A. Research Contributions

In this work, we formulate the spectrum allocation problem as two optimization problems: first with the objective of maximizing the overall spectrum demands (*Max-Demand DSA*) satisfied among various base stations such that no two interfering base stations that belong to different radio infrastructure providers are assigned the same channels and the second with the objective of minimizing the overall interference (*Min-Interference DSA*) in the network when all the demands of the base stations are satisfied. We show that both the optimization problems are NP-Hard1 and design efficient algorithms to solve them. We also design an algorithm with a constant factor approximation that depends on the number of channels available for the *Min-Interference DSA* problem. We report simulation results on sample network topologies to show that our algorithms scale very well for large network sizes.

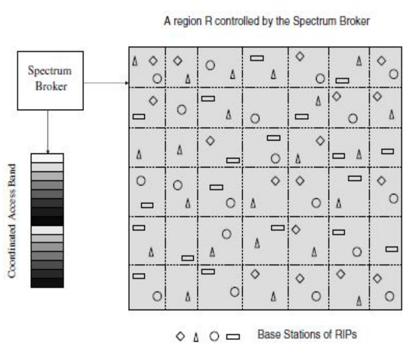

Fig. 2. System Architecture

The rest of the paper is organized as follows: Section II describes the reference system architecture for which the
Problem of spectrum allocation needs to be solved. In Section III, we present our network model and formulate our spectrum allocation problem as two optimization problems. In Section IV, we design efficient algorithms for the spectrum allocation problem. In Section V, we provide detailed performance evaluation of our algorithms. We discuss related work in Section VI. Section VII concludes the paper and outlines our future work. In this section, we describe the reference system architecture for our spectrum allocation problem and discuss the constraints that need to be satisfied by the spectrum allocation algorithms. The discussion here closely follows the model outlined in [2]. In this model, a part of the spectrum, designated as the Coordinated Access Band (CAB), is meant to be dynamically [1] shared under the control of a spectrum broker. Regulatory authorities such as FCC can conduct a one-time auction to license CAB and the winner of such an auction then owns and operates a *spectrum broker* [3]. Each region R, which is under the control of a spectrum broker, can have a number of base stations owned by several Radio Infrastructure Providers (RIPs). The Wireless Service Providers (WSPs) who offer wireless services such as voice, data etc. to the end users are customers of these RIPs and may use different RIPs in different regions and at different times. The network elements such as the Radio Network Controllers (RNCs) that control the base stations aggregate the end user demands and generate a spectrum demand request to the spectrum broker. The aggregation of end user demands can be done either by predicting the expected end user traffic or the end users themselves signal their bandwidth requirement to their respective base stations using a two way control channel. This model differs from existing vertical integration model for cellular networks where each service provider licenses and owns spectrum in a region operates a radio infrastructure and also, offers services to end-users. Our model represents a horizontal model where at the top-level, spectrum access is managed by spectrum provider (the spectrum broker owner), spectrum is used by another level of providers – the RIPs and the end-user services are offered by customer facing WSPs. The portions of the spectrum that are highly underutilized or unused in spatial or temporal dimension qualify as prime candidates to be used as CAB. Examples of such spectrum bands 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)). One can conceivably designate existing cellular bands in 450 MHz, 800 MHz, and 1.9 GHz range also as CAB bands. However, we believe that this move, though technically feasible, may not serve the short-term interest of the incumbent wireless service providers who have spent billions of dollars licensing and deploying their networks and services As such we advocate a *hybrid* model, wherein the existing cellular bands serve as guaranteed capacity or baseline allocation for the incumbent cellular providers and no new providers can avail this spectrum as guaranteed today by the license regime. The CAB band spectrum, however, is guaranteed time bound dynamic access shared among competing providers. This enables existing providers to use CAB spectrum to add capacity to their networks for alleviating traffic hot spots. On the other hand, it also enables new, potentially regional metro scale radio infrastructure providers to compete without requiring large investment in long term licenses of today. This model satisfies several goals advocated by FCC Spectrum Policy Task Force Report [1]. It improves spectrum access in spatial-temporal scale by promoting time-bound access. The spectrum broker can employ market based mechanisms (e.g.: auctions or peak load pricing or hybrids [2]) to price spectrum access. Also, as the broker is cognizant of

spectrum demands over time and space, it can better optimize allocation and improve spectrum utilization which is in contrast to state-of-the-art, where a license holder's spectrum may be underutilized in time and space. Our model provides a practical way to protect incumbents and introduce a graceful DSA mechanism in cellular networks. We designate the smallest amount of contiguous spectrum that can be requested via CDSA as a *channel* of *C* units. If the broker manages a spectrum band of *B* units, it can dynamically allocate $K = B/C$ channels.

V. ALGORITHM

1. When a cell i requires one or more free channels, it sends a request message to every cell in its request set R i, also sets it's pending flag to indicate the pending request.
2. After cell i has received a grant (G i) message from every cell j in R i, it performs the following:
a. Compute $G = \{Gj : j(EGi)\}$
b. Select a set, Gí of the channels in G according to some policy.
c. Send an information that (Gí) channel is busy to every cell in I i.
d. Clear the pending flag. If F=j, then the search fails and acquire (Fí) message is also null.
3. When cell i wants to free channel c, it sends a release message to every cell in I i.
4. On receipt of a request (r) message, cell i places the request in a request list L i.
5. Cell may grant j is request in Li if both of the following conditions are satisfied:
a. Either cell i has no interference with j or it has no pending request of higher priority.
b. F i is null, where F i is the set of all channels x such that none of the cells in CRU i (x) has interference with cell j.When granting j is request, cell I performs the following:
c. Send a grant (F i) message to cell j.
d. Remove j is requests from L i.
e. If j Œ S i then add j to CRU i (x) for each x in F i.
6. When cell i receives a release (c) message from cell j, it removes j from CRU i (c).
7. When cell i receives an acquire (F×) message from cell j, it removes j from CRU i (x) for every x Œ F i j -F×.
8. If cell i is unable to grant a request in Li within a pre specified amount of time, it rejects the request by sending a reject message to the requesting cell and removes the request from Li.
9. When cell i receives a reject message, it aborts its request by clearing the pending flag and sending a revoke message to every cell in Ii.
10. When cell i receives a revoke message from j, it performs the following:
a. If j is request is still in Li, then send a reject message to j and remove the request from Li.
b. Else, remove j from CRUi (x) for every x in F i j.
11. If site i aborts a request; it cannot generate another request until after it has Received a response from every site in Ri.

VI. CONCLUSIONS AND FUTURE RESEARCH

Under the traditional spectrum management framework, interference protection was provided via separation: wireless users were segmented into minimal allocations of spectrum frequencies, exclusively dedicated to non-interoperable, single-purpose wireless technologies. This approach is no longer viable in light of growing demand for spectrum access rights from an ever larger number and diversity of wireless devices. The radio frequency spectrum will have to be shared much more intensively than has been possible with legacy technologies, business models, and regulatory policies. A paradigm shift is necessary to enable a wireless future of greatly expanded wireless usage and advanced capabilities required by our information-based economy and society the need for this paradigm shift is especially acute in the public safety community. The legacy regime severely limits interoperability among first responders and with those they need to communicate with. The fragmentation of infrastructure into incompatible silo-based networks drives up costs, reduces available capabilities and capacity, and ultimately, harms the ability of public safety professionals to do their jobs. In the post-9/11, post-Katrina world, it is clear that we need much greater coordination and real-time advanced communication capabilities available to our public safety professionals. Professionals from different departments and jurisdictions need to be able to talk and interactively share data (including video) quickly, reliably, *and* wirelessly. We want our public safety professionals to be able to respond wherever, whenever the need arises with the appropriate tools to complete their mission of saving lives and property. Meeting the expanded mission requirements will require significant investment in new infrastructure to expand system capabilities and capacity. The traditional approach of over provisioning static network infrastructure to meet worst-case scenario needs is neither feasible nor desirable.

Luckily, it is also no longer necessary. Dynamic Spectrum Access (DSA) technologies like software/cognitive radio (CR) are making it feasible to share spectrum much more intensively. Transitioning to a radio future of DSA/CR will allow radio systems to be much more flexible and adaptable to local conditions. This will increase system capacity and capabilities, enhance interoperability and reliability, and will lower costs. While the wireless future is bright, getting there will not be easy. A new ecosystem of wireless devices, usage and business models, and spectrum policies are needed to supplant the legacy ecosystem. While limited in capabilities, legacy systems have become essential to meeting current requirements. Coordinating the design, investment, and deployment of new technologies without disrupting existing operations will be challenging. Even if all of the requisite technology existed and were commercially available at scale – which is far from the reality today – we would need to reform business models and spectrum management policies to enable use of the technologies. One important and necessary first step toward building the wireless future is to transition to spectrum pooling. Public safety users should pool their spectrum to expand their effective access rights and facilitate the adoption of DSA/CR wireless technologies. As we explain in this paper, this will offer important benefits for public safety systems and is consistent with the trajectory of wireless innovation and growth more generally. Significant progress has already been accomplished toward 4establishing the institutional and policy-framework to successfully implement the spectrum pooling concept. The National Response Framework (NRF), the National Incident Management System (NIMS), the Incident Command System (ICS), frequency coordinators and the Regional Planning Councils (RPCs) provide some of the glue and apparatus needed to coordinate and manage pooled spectrum. We identify other essential components (e.g., agreement on prioritization policies to manage shared access) that must be developed and challenges overcome (e.g., mobilizing coordinated adoption of DSA/CR technologies) along the path to next generation public safety communication systems. To maximize the likelihood of a successful transition, we believe it will be important to move incrementally. If public safety professionals are to be convinced that spectrum pooling is indeed a concept whose time has come, they will need assurance that they will not experience any degradation in current capabilities or loss of resources. Future progress will build on early experience and learning. Over time, however, we expect the spectrum sharing concept to be generalized. All future wireless systems should be more dynamic and capable of interacting with expanded notions of priority in spectrum access rights. Public safety users may start out by reciprocally enabling secondary use of their dedicated spectrum bands by other public safety first-responders, then expanding to other government agencies and non-government affiliates, and ultimately, to commercial users/uses. The increased sharing of infrastructure and resources will benefit all if implemented appropriately. Public safety provides an important first test case for commercialization of these sharing ideas as we have explained herein, and success here will deliver positive externality benefits for the wider adoption of DSA/CR more generally.

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