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SPECTRUM SHARING THROUGH DYNAMIC CHANNEL ASSIGNMENT FOR OPEN ACCESS TO PERSONAL COMMUNICATIONS SERVICES

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Abstract. This paper focuses on a narrow band technical solution that uses decentralized spectrum sharing to facilitate open access among competing Personal Communications Services (PCS) operators. Existing policies that apportion spectrum by Fixed Channel Assignment (FCA) involve inefficiencies resulting from fragmentation of the available resource into mutually exclusive frequency blocks. Dynamic Channel Assignment (DCA) has been previously demonstrated to be flexible in handling traffic variability and to simplify frequency planning for a single network operator. In this paper we use a discrete event simulation to demonstrate that DCA with Autonomous Reuse Partitioning (ARP) provides more capacity than standard DCA; this property still holds when channels are shared among multiple operators, with partially overlapping networks and unequal traffic shares. We explore the impact of limiting the maximum number of channels that can be assigned to one cell site as an incentive for operators to build more cells, rather than simply appropriating channels from competitors.

1 Background.

Spectrum allocation policies of the Federal Communications Commission (FCC) direct the following: 1) the class of use for a particular portion of the spectrum (frequency allocation), 2) technical rules governing characteristics such as channelization, power levels, or modulation, and 3) who may use the limited spectrum available (frequency assignment). Spectrum allocation decisions of the FCC determine the structure of an industry: in cellular telephony, the FCC has created duopolies in each region by allocating spectrum to only two providers; with its proposed PCS allocation rules there may be up to seven additional competitors in a given area. In this paper, we consider whether it is technologically feasible and efficient to establish new policies governing spectrum use. One such group of PCS policies are known as "open entry" or "open access" [1,2], which means an unlimited number of firms can compete for providing Personal Communications Services.

An open entry approach to PCS means that a mixture of electronics and market forces, rather than federal regulations, would determine the optimal number of competitive suppliers of PCS services in each market. Open entry would permit the maximum sustainable levels of competition, with all the benefits that a market based scheme provides in driving down prices. Using open entry can allow for more efficient spectrum utilization, as compared to licensing fixed bandwidth allocations to PCS competitors regardless of their market share.

Spectrum may be shared among multiple operators through Dynamic Channel Assignment (DCA). DCA has been discussed in the literature as a way to achieve improved resource management and "self-planning" within a given operator's network [3, 4]. Under DCA, channels are not permanently assigned for use by a particular base station, but are allocated dynamically as calls appear and are terminated. By comparison with Fixed Channel Assignment (FCA) DCA not only allows significant capacity gains due to superior frequency reuse, but also mitigates efficiency losses arising from time-varying traffic spatial distribution. DCA can not only be used to allocate channels among the base stations of a single operator but among those of competing operators as well, as is shown in this paper. Section 2 addresses limitations and alternative DCA strategies, Section 3 structures the problem and explains the simulation model, Section 4 presents research findings, finally Section 5 brings the main policy conclusions.

2. Dynamic Channel Assignment

Under DCA, channels must be assigned on demand in a way which limits co-channel interference to acceptable levels. Takenata et. al. [5] have grouped channel assignment strategies into three categories:

• Minimum reuse distance strategies will not assign the same channel to any cell that is within a certain distance of a reference cell to which the same channel has already been assigned [6]. This method may require extensive communication among base station controllers.

• Adaptive Decentralized strategies assign intended channels relying on local information about signal levels and interference. This information can be measured at the base station, handset, or both [7]. Any one of several algorithms is used to autonomously select a channel with an acceptable signal to interference level. For example, the channel with the highest Carrier-to-Interference Ratio (C/I) might be chosen.

• Optimization strategies employ linear programming or neural networks to re-configure the entire system each time a new channel assignment is made. The objective is to maximize a figure of merit such as overall system C/I. Such methods are computationally intensive and require centralizing real time C/I information which has been collected at each mobile or base station[8, 9].

We focus our attention on an adaptive decentralized strategy known as Autonomous Reuse Partitioning (ARP) [10]. With an ARP algorithm, all base stations search channels in the same order and assign the first channel that meets a minimum C/I threshold to the call. Since users close to a base station are more likely to have a higher C/I ratio, channels which are high on the list are often assigned to calls originating near the base station; channels farther down the list are assigned to calls originating near the cell boundary. The effect of ARP is equivalent to increasing frequency reuse by sectoring cells as concentric rings. In spite of its simplicity, ARP provides superior performance to alternative strategies like minimum reuse distance, and does this without demanding information exchange among operators.

Transmitter Power Control (TPC) at the base station and at the mobile can further improve frequency reuse by limiting the *Effective Isotropic Radiated Power* (EIRP) to the minimum necessary for achieving a satisfactory C/I. TPC can be designed to maintain either a constant power level at the distant receiver, or a constant C/I ratio [11, 12]. The latter is understood to be more efficient, but on the other hand power control feedback may produce system instability.

2.1 DCA, TDMA and CDMA

Digital technologies such as *Time Division Multiple Access* (TDMA) and narrow-band Code *Division Multiple Access* (CDMA) employ a single *Radio Frequency* (RF) carrier or bearer for multiplexing voice channels. For reasons related either to synchronization in TDMA or the near-far problem in the case of CDMA [13], an entire RF carrier capable of accommodating multiple users must be assigned to one operator at a time. This introduces a fragmentation problem which reduces the efficiency of Dynamic Channel Assignment in these cases[14]. For the U.S. IS-54 TDMA standard [15], which provides for only three users per RF carrier, the problem is not as severe as for GSM. Our analysis looks only to *Frequency Division Multiple Access* (FDMA).

2.2 Limitations of DCA

In a DCA open access environment, operators share a common pool of channels supporting their respective customers. As usage increases, the channels are occupied and cells must be made smaller to increase system capacity through frequency reuse. Because the spectrum is shared, the firm investing in new cell sites bears the costs, but the investment benefits all operators. Consequently, there is a risk that this mismatch of costs and benefits leads operators to seek a "free ride" and claim more channels from the common pool rather than build more cell sites [16]. This social dilemma is known in the literature about resources allocation as "The Tragedy of the Commons" [17]. Recent academic research has shown (through computer simulations) that, in the absence of central authority, social systems converge towards cooperation in the long term after experiencing random fluctuations [18].

A related problem concerns quality of service guarantees. Since all operators share a common pool of channels, exhausting the available channels will force operators to block additional calls. There is no way for a given service provider to position itself as a "high quality of service" operator; all operators end up with virtually the same blocking probability. Even if an operator decides to build extra cells to create more capacity through frequency reuse (and decreasing power at the base stations through TPC), that additional system capacity is available to all operators through DCA. Finally, DCA requires cell sites to be equipped with enough hardware to transmit at any frequency, as opposed to FCA where only a subset of channels is handled at each cell. Furthermore, sufficient radio ports and trunking facilities to the switch must be in place at a cell to handle the peak traffic loads and take advantage of DCA's surges capabilities. This can increase fixed costs at each cell as compared to FCA. Ways to cope with issues of "The Tragedy of the Commons" and reduce the number of transmitters will be addressed in § 4

3. Simulation Model

Dynamic Channel Assignment (DCA) with Autonomous Reuse Partitioning (ARP) has been shown to provide excellent spectrum efficiency when employed by a single operator. If multiple operators dynamically utilize channels from a common pool, is efficiency reduced, increased, or does it remain unchanged? To investigate this question, we simulated the performance of a PCS system (involving from one to four operators) and compared the results. Our model evolved from the

DCA simulation code developed by K. Sivarajan [19], and further incorporates ARP and TPC. Mobiles were assumed to be quasi-stationary, and hand-offs were not modeled. The simulation employs an 8x8 grid of hexagonal cells which are folded over onto the surface of a torous to avoid edge effects, and allowing data to be collected over all cells. In order to study the effects of being near or far from the base station, calls were assumed to originate at one of 64 discrete grid points uniformly distributed throughout a cell. Signal strength was assumed to decline with the fourth power of the distance between transmitter and receiver [20, 21]. Our propagation model assumes deterministic signal levels. Other key assumptions are listed in Table 1.

Table 1. Model Assumptions

Exponential call inter arrival and call holding times
Blocked calls lost
Homogeneous traffic spatial distribution
Ideal control of received power level
Frequency Division Duplex (FDD) channels
Asymmetrical up and down link interference
50 available channels
Dynamic Channel Assignment with TPC and ARP

As calls arrive, both the mobile and base station begin searching though an ordered list to find channels for which the C/I ratio exceeds a pre-defined threshold. For a digitally encoded voice channel, such as the DCS1800 PCN, 9 dB has been found to be an acceptable level for satisfactory service quality [22, 23].

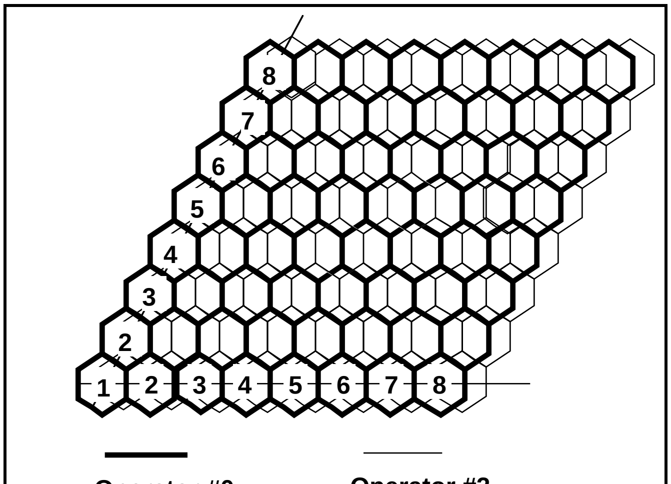

Figure 1. Cell Layout for 2 Overlapping Operators

We set the call threshold at 11.32 dB to provide an additional margin against interference from calls accepted subsequent to this assignment [24]. In a DCA system, subsequent calls elsewhere in the system on the same channel, while having an acceptable C/I ratio themselves, may lower the C/I ratio of an ongoing call to an unacceptable level.

Calls which experience interference while in progress must be handed off to a different channel; the call may be dropped if no available channel is found [25]. By setting the call blocking threshold above the minimal acceptable quality level, the need for subsequent hand-offs is reduced. In practice, C/I levels can be determined by independent measurements of I and C+I, or from signal quality statistics derived from the demodulator [26].

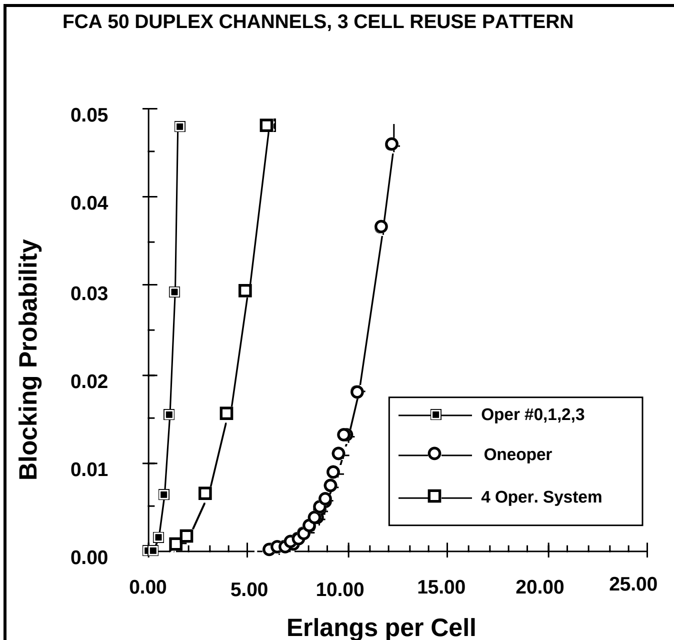

Figure 2. Trunking Inefficiencies with FCA: theoretical performance of a monopoly operator (Oneoper) vs 4 competing operators (Oper# 0,1,2 and 3) and system behavior (4 Oper.System).

We considered the cases of single versus multiple operators. If four operators had collocated base stations, we would expect performance identical to that of a single operator. Thus, cell layouts of the four operators are assumed to be offset with respect to each other (Figure 1). Call arrivals are assumed to be unequally partitioned among the operators; each one of the four operators handles 50%, 25%, 16.7% and 8.3% of the total load respectively. In the next section we show that even in the more difficult case of unbalanced traffic, the system with four operators uses spectrum as efficiently as a single operator. We validated the model for the single operator case by comparing the output with the results obtained by Sengoku [27] and the analytic approximation models of Cimini and Foschini [28].

4. Results

Figure 2 shows traffic performance for 1 and 4 FCA operators, assuming equivalent traffic shares (which is the best case for FCA) and exclusive allocation of equal portions of the available bandwidth (50 channels).

Blocking probability is plotted against Erlangs of traffic per unit area at both individual operator and total system levels. FCA's trunking inefficiencies greatly reduce overall performance. Note that overall trunking inefficiencies are less severe when the total number of channels in the system is increased. (See ref. 13 for the inefficiencies of FCA with 832 channels). Figure 3 compares the performance of one operator versus four operators assuming DCA and ARP. Traffic is assumed distributed asymmetrically among the four DCA operators as described in §3.

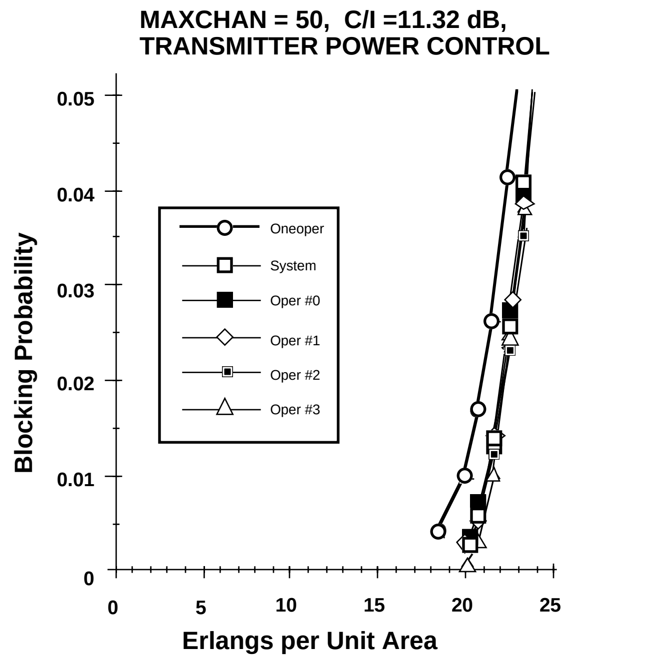

Figure 3. ARP DCA, four non-collocated operators, and no restrictions in the number of available transceivers.

Using a one sided t-test, we can reject the hypothesis that multiple operators degrade performance relative to a single operator at the .00005 level. Not only is there no reduction in efficiency, but traffic handling capability is actually larger in the multioperator case. We attribute this to improved frequency reuse, due to a greater overall number of base stations from multiple providers; consequently smaller coverage areas result from a combined effect of service area overlap and TPC.

4.1 Interference with Calls in Progress

As noted above, calls in progress may experience co-channel interference from subsequent calls in neighboring cells. For a single operator, at 20 Erlangs of traffic per unit area and a blocking probability (Grade of Service GOS) of 1%, 17% of the calls in progress dropped below the 9 dB service quality standard. These calls would need to be handed off to a different frequency; sometimes a hand-off would be impossible and the call would be dropped while in progress. However, we have not modeled intra-cell hand-offs in this study; so the simulation kept calls in progress despite slight degradations in C/I.

4.2 Sensitivity Analysis

The probability of call interference can be reduced by raising the C/I threshold needed for accepting a call on any channel, with a corresponding reduction in traffic handling capability. We used a higher threshold of 14 dB, for a single operator which reduced capacity by 27% at a 1% GOS, but also reduced interference to calls in progress to 5%. For example, assuming intracell hand-off was implemented with a 90% success ratio, the number of calls dropped would be 0.5 % of calls in progress.

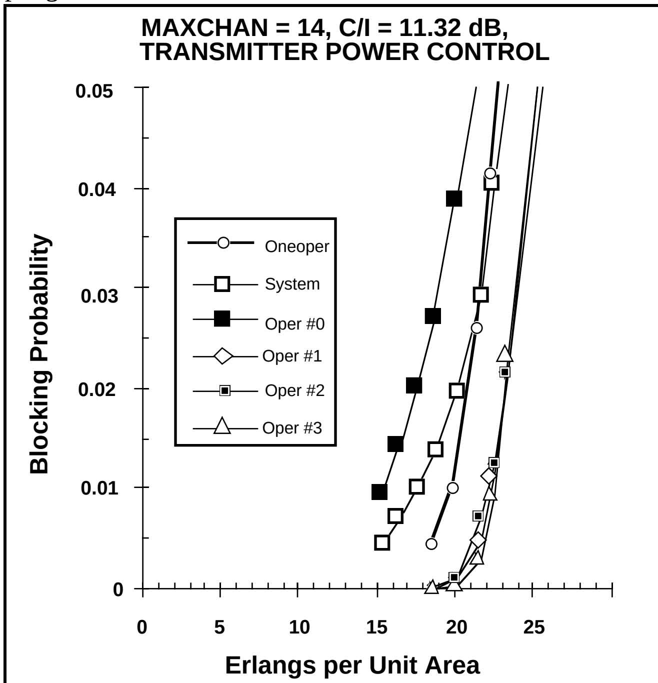

Figure 4. Performance of DCA ARP when the number of active channels is restricted to 14.

4.3 Limitations on Transceivers per Base Station

The results presented above assumed every base station had 50 power controlled transceivers, enough to handle high traffic loads spatially concentrated in a single cell. If transceivers and trunks per cell are limited, (e.g. to reduce costs} what impact does that have on performance? Using FCA and a reuse pattern of K=3, each base station would be equipped with no more than 17 radios. In Figure 4, we compare a single DCA operator using ARP and having 50 transceivers per port, to a multi-provider scenario where each operator's base station has no more than 14 autotuned transceivers. For a 1% GOS, the average system performance with four operators "transceiver-constrained" is only slightly less than the performance of a single, unconstrained operator.

Note that the impact of transceiver constraints falls most heavily on the operator with 50% of the traffic, while the operators with less than 25% have capacity to spare. These results suggest a possible approach to the disincentive to deploy base stations problem described in §2. By limiting, via regulation, the number of transceivers per base station, operators have an incentive to build more cells as their traffic grows, since they cannot simply grab more dynamically assigned channels.

5. Conclusions

Our results suggest that Dynamic Channel Assignment could provide the basis for an autonomous open access approach to narrow band PCS spectrum management. DCA-based open access allows market entry to any number of potential PCS providers. It eliminates wasted capacity or the problems of adjusting fixed spectrum allocations as the market share of a particular provider ebbs and flows. Multiple firms sharing spectrum through DCA use it as efficiently as a monopolistic entity would.

The benefits of DCA, even for a single operator, make it likely that some form of DCA will be implemented by providers in the long term; *e.g.* DCA greatly simplifies channel assignment in micro cell networks. The biggest drawback to open access DCA is that it limits the ability of firms to compete on the basis of premium blocking probability, since the actions of competitors will influence the blocking probability of each service provider. This is in stark contrast to fixed frequency allocations, where each provider can control the level of blocking by its deployment of additional base stations.

Our analysis has several assumptions that need to be relaxed in future work. First, we should consider whether non-deterministic path loss models would change our conclusions about one-vs.-many. Second, our simulation model assumes one channel per frequency; carrier fragmentation effects in assigning TDMA and CDMA bearers needs to be explored further. It is possible that a channel segregation scheme [29, 30] for carrier assignment would largely mitigate these fragmentation effects. In addition, synchronization becomes an issue with TDMA autonomous systems [31].

Finally, policies for overcoming negative externalities problems with DCA need to be elaborated upon and analyzed in more detail. Our suggestion of limiting by regulation the number of autotuned transceivers per base station needs to be examined for enforceability, side effects, implications of sectorization, and general practicality. "Tragedy of the Commons" problems are best solved by setting a price on the use of the common resource; in this case, the government might fix charges on spectrum usage. Fees could be based on utilized bandwidth (number of transceivers) and EIRP. Certain degree of GOS differentiation can be allowed by reserving a block of channels exclusively for overflow traffic, and by imposing incremental fees on the extra transceivers required for this purpose. Whether such regulatory schemes could be made practical needs further exploration. For the allocation of an unlicensed PCS band, the U.S. Federal Communications Commission has endorsed an unlicensed spectrum etiquette. This etiquette employs a figure of merit based on EIRP versus bandwidth for spectrum sharing among multiple users with dissimilar technologies [32].

We note that nothing in the current U.S. FCC policies would prevent the licensee of an exclusive spectrum allocation from subletting its spectrum to multiple operators in a shared basis, and implementing open access trough a common standardized air interface, within the assigned bandwidth.

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