

# Dynamic Sharing of Radio Spectrum: A Brief History

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This was written a few years ago as a chapter in a book—  
but that book ended up not being published.

Thus it is a little out of date in places.

Please send any comments to me at [chuck@jacksons.net](mailto:chuck@jacksons.net).

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Charles Jackson

301 656 8716

[chuck@jacksons.net](mailto:chuck@jacksons.net)

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## I. Dynamic Sharing of Radio Spectrum: A Brief History

### A. Introduction

This article reviews the various approaches to dynamic sharing of spectrum that have been employed over time, identifies the costs and benefits of these approaches, and offers conclusions on the characteristics of radio services that benefit most from the use of dynamic sharing.

I use the term *dynamic sharing* to refer to spectrum access systems that maintain the spectrum resource in a pool and permit users to access it on a demand basis. Such demand sharing may be mediated by protocols alone or may include regulatory intervention (e.g., changing regulatory constraints in response to congestion) or market mechanisms (e.g., peak-load pricing of the spectrum resource). Dynamic sharing is not new; radio operators have used dynamic sharing from the beginning of radio communications.

As stated above the general idea of dynamic sharing is the concept of a pool of capacity that is allocated on demand. The British CT2 (second-generation cordless telephone) provides a good illustration of dynamic sharing. CT2 cordless telephones are allocated 4 MHz of spectrum, divided into 40 channels. When a CT2 base station receives an incoming call and must establish a connection to its associated portable handset, it scans all 40 radio channels in order either to find a vacant channel or to identify the channel with the weakest signal present. The base station then begins the conversation with the portable unit using a channel identified in this process. The dynamic allocation approach used by CT2 phones provides reasonably efficient spectrum utilization at affordable costs. Consumer cordless telephones automatically avoid the frequencies used by neighboring cordless telephones.

The CT2 technology provides a specific example of dynamic sharing that uses time-varying frequency-division multiplexing. Of course, the system element that varies with time need not be the frequency-division plan; the time variable element might also be based upon time division or code-division

techniques or a mix of techniques. Below I consider several examples of dynamic sharing. Some of these examples currently exist only as plans or proposals; others have operated for many years. Some were technical and regulatory successes, other were failures.

## **B. Specific examples of Dynamic Sharing**

Many radio systems employ forms of dynamic sharing. The discussion below describes several of these systems with particular attention to the sharing rules. Systems are listed in the approximate order in which they were developed.

### **1. Traditional maritime radio**

From the very beginning of wireless telephony maritime radio has always used shared channels. For example, 2,182 KHz is used as a calling frequency as well as an emergency signalling frequency and other frequencies are used as working frequencies. Ships keep watch on 2,182 KHz. If Ship A wishes to communicate with Ship B, Ship A identifies a working frequency and then places a call to Ship B on the calling frequency (e.g., 2,182 KHz). Communications on the calling frequency serve to alert Ship B that Ship A is calling and to tell Ship B which working channel is to be used.<sup>1</sup>

The benefits of such rules are obvious. Specifying a channel (or channels) that ships keep watch on facilitates both emergency signalling and establishing connections between ships. Channel sharing was necessary and effective because there were not sufficient channels to give each ship a separate channel and the typical ship required far less than a full channel of capacity.

To appreciate the economics of this sharing technology, consider that a single-channel Morse code receiving system was expensive—requiring both a radio and a human operator. Ship operators could not economically keep watch on many different channels. Selecting a single channel for call setup and

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<sup>1</sup> See Radio Regulations 60–71 (1) and (2). Edition of 1982.

for emergency calling allowed efficient telecommunications and provided support for the important function of monitoring for emergency transmissions. Note that such monitoring creates important externalities but does not benefit the ship providing the monitoring service. Combining the shared setup channel for commercial traffic with the emergency channel reinforced the regulatory obligations to maintain watch on the distress frequencies with commercial incentives to monitor incoming messages.

## 2. Traditional Land Mobile Radio

The FCC has long authorized the use of shared channels in land mobile. A typical example from the 1960s would be a single channel covering a city and being used by both a plumbing company and a pizza delivery company. Neither firm has sufficient demand to justify an entire channel, yet each firm benefits substantially from mobile communications. Simple protocols (listen before talking) and short messages allow for reasonably efficient sharing of a single channel using the single-channel FM technology of the time. With slightly more complex gear (e.g., tone-coded squelch), it was possible to shield the plumbers from the pizza delivery messages and vice versa.

## 3. FCC's Open Entry for RCCs on Docket 18261 Frequencies

In the mid-1970s, in order to expand land mobile service, the FCC permitted land mobile operation on some of the lower UHF channels in several large cities. One group of channels was made available to Radio Common Carriers (RCCs) to provide mobile service on a common carrier basis. The FCC adopted rules permitting open entry for these channels and requiring carriers to monitor the channels and select an unused channel to carry each conversation. In essence, exclusivity was provided on a first-come, first-served basis one conversation at a time. See 47 CFR 22.501(j). As I understand the outcome, these rules did not promote true open entry in practice. Rather, in those cities where multiple carriers were interested in providing service on these channels, the carriers got together and built a single, shared system.

In retrospect, these rules involved too little spectrum (roughly 12 channels in each of 10 cities) to justify either special investment by hardware manufacturers or system operators.

#### 4. Britain's CT2

In the mid-1980s, British industry and government, working together, developed a new standard for digital cordless phones. This standard became known as *CT2*, an acronym of sorts for Cordless Telephone, 2nd generation. *CT2* was designed for use in both the home and in a public mode—a cordless payphone—known as Telepoints. *CT2* uses a pool of 40 channels. To establish a call, the equipment automatically identifies a vacant channel or the channel with the least interference and begins operation on that channel. In low-usage areas, the dynamic channel selection rules embedded in the *CT2* equipment ensure that *CT2* systems do not interfere with each other. One person's *CT2* system won't ever interfere with a next-door neighbor's *CT2* system. In high-usage areas, *CT2*'s dynamic sharing rules act to shrink the reliable service range of *CT2* systems, but preserve the basics of the service. Providing similar exclusivity through the traditional approach of maintaining a coordination database, searching the database for vacant channels, and preauthorizing transmitters appears to be far more expensive than the distributed, real-time algorithms of *CT2*.

*CT2* service, especially the public Telepoint service, failed to catch on in the U.K. However, *CT2* was extensively used in Hong Kong and Singapore. Its dynamic sharing rules work in practice. There appear to be two keys to the success of the *CT2* rules. First, the sharing rules were well engineered and implemented. Second, interference between *CT2* systems is symmetric—the level of the interfering signal user A transmits into user B's system is roughly equal to the interference B generates into A's system. Hence, interference is effectively internalized. Third, a user can increase the interference rejection capabilities of his or her system by moving the portable unit closer to the base station.

## 5. Part 15

The FCC permits unlicensed operation under Part 15 of its rules. Part 15 covers the use of low-powered devices such as garage door openers. Part 15 also covers the more interesting use of higher power spread-spectrum devices operating in the ISM bands. Part 15 spread-spectrum devices operate at powers of up to one watt. One watt is sufficient power to give a range of several miles. Part 15 spread spectrum is being used for wireless LANs and high-performance cordless telephones. One firm, Metricom, is building a commercial data and Internet access service using a network of unlicensed Part 15 transmitter/receiver units in urban areas. Metricom currently offers service in the San Francisco Bay area, Washington D.C., and Seattle and on some university campuses.

The Part 15 spread-spectrum rules impose limits on power and minimum spreading. These rules make Part 15 spread-spectrum radios reasonably good neighbors with one another. The Part 15 rules do not contain any complicated etiquette governing spectrum access. Indeed, they do not even contain minimal listen before transmitting rules. Nevertheless, they have proven to be enormously workable in practice.

## 6. Abramson's Aloha Channel and Derivatives

In an early research project on radio access to computer systems, Professor Norman Abramson of the University of Hawaii developed the Aloha channel model permitting many remote terminals to share the capacity of a single radio channel using a simple algorithm in each terminal with no central control.<sup>2</sup> Abramson showed that quite simple sharing rules could generate moderate efficiency in channel use. Improvements to the original Aloha channel rules (simple steps such as listening to make sure the channel is free before transmitting) allowed systems to achieve channel efficiencies in the 80 to 90 percent range while still avoiding use of a central system control. The widely used Ethernet technology

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<sup>2</sup> N. Abramson, The ALOHA system -- another alternative for computer communications, in AFIPS Proc. FJCC Conf., vol 37, Fall 1970.

for local area networks is based upon these technologies. This technology allows many computers to share the same network without centralized controls.

An element of central management is needed in pure Aloha networks. An overloaded Aloha network will suffer a form of gridlock and capacity will fall to zero. Variants of Aloha have the property that they continue to carry traffic when overloaded. But, even with these improved systems, when overload occurs, all stations start to experience delays.

One of Abramson's contributions was to show that simple sharing rules—rules that could easily be implemented in low-cost terminal equipment—could lead to efficient use of both the radio channel and any expensive base station equipment associated with the channel. The use of similar radios and the same channel access algorithm provided symmetric interference between stations in the Aloha channel model.

## 7. Air-Ground Telephone Service

The FCC's rules for the 800 MHz Air-Ground Telephone Service (47 CFR 22 Subpart M) give each licensee exclusive access to a dedicated control channel (for setting up calls) and shared access to a pool of working channels (for carrying conversations). When it initially defined the rules for this service, the FCC specified channel plans and technical rules for indicating when a channel was free. But the Commission allows the operators in the band to adopt new channel plans and related technical rules upon mutual agreement.<sup>3</sup>

The air-ground telephone service is a success. Multiple vendors provide air-ground telephone service. Those suppliers face the threat of competitive entry. As with CT2, several factors combine to make this licensing regime work. Interference is roughly symmetric, thus internalizing interference costs. Second, only a few operators offer this service so that coordination problems are not excessive.

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<sup>3</sup> See 47 CFR 22.1107 and 22.1115.

## 8. Jackson's 1991 PCS Proposal

In his testimony at the FCC's 1991 PCS en banc meeting, Dr. Charles Jackson suggested an open entry policy be used for commercial PCS operations. He said:

Open entry refers to a combination of technology and policy that allows the FCC to license a large, perhaps unlimited number of system operators, and to have the technology able to operate efficiently in this environment. Clearly to do this the technology must have some way to divide the spectrum among the system operators. The U.K. CT-2 design offers one way to do this. CDMA and variants on traditional cellular offer others.

A key issue in any open entry scheme is avoiding the "Tragedy of the Commons" whereby a public resource is overused since each individual user has not incentive to conserve. . . . Consider an open entry scheme using CDMA. As PCN usage increased in a community, the FCC could lower the maximum allowed power for mobiles. Service ranges would decrease and all carriers would have equal incentives to split cells. Under such a limit the FCC would not have one firm running higher power portables and stealing the common spectrum from others. But, if the FCC did not regulate power or average power, each system operator would have an incentive to delay cell splitting to save on costs. Those firms that did split cells and reduce power would reduce interference to themselves and to others in the band. Such unbalanced external effects are exactly the conditions that lead to the problem of the commons.<sup>4</sup>

While the FCC chose to allocate 20 MHz of spectrum for unlicensed PCS under rules that assured equitable spectrum access by unlicensed devices, it did not seriously consider Jackson's plea for open entry followed by regulation of technology to assure equitable sharing for PCS service providers.

## 9. Big LEOS

The FCC authorized three large-scale low-earth-orbit satellite systems (called big LEOS), Iridium, Globalstar, and Odyssey. Iridium, an FDMA system, has been assigned its own dedicated spectrum.

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<sup>4</sup> Written Statement of Dr. Charles L. Jackson, FCC PCS en banc hearing, December 5, 1991, footnotes omitted.

Globalstar and Odyssey are both CDMA systems and were assigned shared spectrum. Consider the benefits of this FCC policy. All three firms had the opportunity to bring their designs to the market—at least to the financial markets—and see how well those designs fare. If the FCC refused to license until all financing were complete, the added uncertainty associated with future licensing would make it harder to raise the financing. The sharing rules will permit either Globalstar or Odyssey to exploit the entire CDMA subband until the other system becomes operational.

#### 10. Unlicensed PCS

The FCC set aside 20 MHz of PCS spectrum, 1910 MHz to 1930 MHz, for operation of unlicensed systems. The 20 MHz band is divided into two equal subbands—one for bursty computer data, the other for continuous signals such as speech. FCC rules specify how equipment shall search for vacant channel space in the band. These rules are similar to those of CT2, although more complex, and include rules for random retries in the fashion of the Aloha channel.<sup>5</sup>

Some products for unlicensed PCS have been announced, and UTAM is in the process of coordinating the operation of unlicensed PCS with the existing OFS microwave systems in the band. Perhaps the most interesting feature of unlicensed PCS is the decision to place the quite different voice and data services in separate bands rather than to allow dynamic sharing between unlicensed voice and data services in a single band. The pressures for this decision appear to come from recognition that the interference between these two services would not be symmetric.

#### 11. Apple Computer's NII Band

On May 24, 1995, Apple Computer filed a petition for rulemaking with the FCC, requesting the FCC to establish an unlicensed, high-capacity band for wireless data—a proposal they christened as the *NII band*. This proposed band would be similar to the data portion of the unlicensed PCS band, except

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<sup>5</sup> 47 CFR 15.321, 47 CFR 15.323

that it would have far greater capacity. Apple's NII band would use frequencies allocated for unlicensed wireless local area networks throughout most of Europe, thus allowing international roaming with nomadic computing devices.

Apple's petition discusses the sharing rules needed to assure efficient and equitable access to the NII band.

The success of the NII Band depends upon the adoption of a set of operating requirements to govern unlicensed use of the frequencies . . . The rules governing the NII Band must assure that all devices retain an equitable right to access and share the spectrum resource. In particular, they must prohibit any rules for operation which are based upon (or display the preclusive behavior of) a circuit-switched network, as well as any requirement (or exceptional priority) for centralized gatekeepers. . . . Even with a suitable allocation, however, there may be circumstances in which overcrowding occurs, In such cases, it is imperative that all communications share this burden equally, (through delays in transmission times), rather than permitting some types of applications to monopolize the network at other's expense.

Apple Petition, p. 25-26, footnotes omitted

Reflecting the debate that led to the separate bands for voice and data unlicensed PCS, Apple requested that the sharing rules be defined in a fashion that is symmetric among all users transmitting packet data.

The FCC created a new unlicensed band, called the NII band, at 5 GHz.

## 12. Gilder's 1994 Proposal

In an article entitled "Auctioning the Airwaves" in the April 11, 1994 issue of *Forbes ASAP*, George Gilder reviewed the development of radios and computers, described with great enthusiasm the radio receiver systems of one particular firm, and suggested that an open entry approach to radio system authorization was superior to the FCC's proposed auctions of PCS licenses. Gilder wrote with his usual flair and punch. The following quotations give the essence of Gilder's position:

The FCC is fostering a real estate paradigm for the spectrum. You buy or lease spectrum as you would a spread of land. Once you have your license, you can use it any way you want as long as you don't unduly disturb the neighbors. You rent a stretch of beach and build a wall.

The Steinbrecher system, by contrast, suggests a model not of a beach but of an ocean. You can no more lease electromagnetic waves than you can lease ocean waves. Enabled by new technology, this new model is suitable for an information superhighway in the sky. You can use the spectrum as much as you want as long as you don't collide with anyone else or pollute it with high-powered noise or other nuisances.

In the Steinbrecher model, you employ the spectrum as you use any public right of way. You are responsible for keeping your eyes open and avoiding others. You cannot just buy a 10 year lease and then barge blindly all over the air in a high-powered vessel, depending on the government to keep everyone else off your territory and out of your way.

With an increasing array of low-interference technologies available, the FCC should not give exclusive rights to anyone. Instead, it should impose a heavy burden of proof on any service providers with blind or high-powered systems that maintain that they cannot operate without an exclusive license, that want to build on the beach and keep everyone else out of the surf. In particular, the FCC should make all the proponents of TDMA, whether in the American or European GSM systems, explain why the government should wall off spectrum. The wireless systems of the future will offer bandwidth on demand and send their packets wherever there is room.<sup>6</sup>

As we all know, the FCC disregarded Gilder's advice and auctioned off PCS spectrum.

Gilder's proposals lack specificity and detail. Importantly, he fails to distinguish between applications such as broadcasting, which can efficiently employ a block of spectrum full time and applications, such as an individual's personal portable radio telephone, that require intermittent access to the spectrum. He did not discuss the problems of asymmetric interference in which application A can work well but

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<sup>6</sup> A copy of the Gilder article is available at <http://homepage.seas.upenn.edu/~gaj1/auctngg.html>. These quotations were taken from that copy.

can deny all spectrum access to application B. Contrast his blind acceptance of a technological quick fix with the more detailed and limited approach in the Apple proposal or in the FCC's air-ground telephone service. Open entry is a workable regulatory approach, but it cannot work in the absence of regulation. Someone must define the rules that assure equal access to the spectrum.

### 13. Noam's 1995 Proposal

Professor Eli Noam of Columbia University proposed a system of *open spectrum access* that he characterized as a step beyond auctions.<sup>7</sup> Noam's proposal was not unlike Gilder's vision—indeed Noam referenced Gilder. After a long discussion of problems associated with auctions and other choice mechanisms, Noam strongly endorsed an open entry approach under which users would seek out and transmit on vacant spectrum. To quote Noam:

Auctions are good for now, but there is a better next step, a free-market alternative to the present auction system: an open entry spectrum system. In those bands to which it applies, nobody would control any particular frequency. . . . There is no license and no up-front spectrum auction. Instead, all users of those spectrum bands pay an access fee that is continuously and automatically determined by the demand and supply conditions at the time (i.e., by the existing congestion in the various frequency bands). The system is run by clearinghouses of users.

As with Gilder, Noam appeared to be thinking more of intermittent spectrum uses such as voice telephony applications rather than enduring uses such as broadcasting.

Noam offered one major advance over Gilder—he suggested that, if congestion occurred, a pricing mechanism—a congestion toll—be applied. Under Noam's vision, the FCC would collect a scarcity rent just as it does today. But collecting that rent could be put off until the scarcity was actually a problem. If six firms could operate PCS systems without interference, then there would be no scarcity and no need for congestion tolls.

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<sup>7</sup> Eli Noam, "Taking the Next Step Beyond Spectrum Auctions: Open Spectrum Access," IEEE Communications Magazine, December, 1995, p 66- 73.

Shortcomings in Noam's analysis include the lack of any consideration of the problem of asymmetric interference or of the problem of defining and monitoring congestion. What congestion fee should a cordless telephone pay if it renders useless the receivers at a three-million-dollar satellite earth station? Noam's approach could probably be applied to radio services characterized by intermittent transmissions and symmetric interference. A rough justice approach to measuring congestion and setting congestion tolls might also work with reasonable efficiency. Noam also does not discuss how usage would be metered and bills rendered. With many radio technologies only a system operator or user has the information needed to calculate the bill for his or her system. Clearly, this creates perverse incentives for record keeping and runs the risk of tempting system operators to cheat.

#### 14. A Related Issue—United States Opposition to A Priori Planning of Satellite Systems

In international negotiations, the United States has been a consistent opponent of a priori planning of satellite systems. Some nations have pushed for an international regulatory regime characterized by preplanning the geostationary arc. Geostationary arc capacity would be divided up in advance and passed out among the nations of the world. The United States has opposed this view and has argued instead for continued flexibility and traditional first come, first served licensing. One building block for the United States position has been that it is hard to forecast future technology and that it is highly likely that future technology (e.g., higher bands, frequency reuse) will expand capacity. Such capacity expansions would reduce or remove any scarcity. In contrast, preplanning the arc, which can only be done using the technology available or reasonably foreseeable at the time of planning, will lock in inefficient technologies and will reserve capacity for systems that will never be built, thus creating multiple inefficiencies and artificial scarcities.

For example, the U.S. proposal for WARC-92 included the following statement:

Because of the demands being placed on the 1-3 GHz spectrum by a multitude of services, we believe it is extremely important to utilize the spectrum efficiently. The

current service specific allocations in the 1.5/1.6 GHz bands are too restrictive to permit flexible usage to adapt to dynamic changes in communications needs.<sup>8</sup>

This U.S. position can be viewed as a form of dynamic sharing but with a time constant of years rather than minutes. Under the U.S. position, the orbital arc is to be shared among the nations of the world in an equitable fashion using the current technology and demands for service.

## C. Discussion

### 1. Successes

As the above examples make clear, various forms of dynamic spectrum sharing have been used in radio communications for almost a century. Dynamic sharing is supported by both theory and practical experience. What are the characteristics of services in which dynamic sharing works and services where it does not work?

1. Dynamic sharing requires some form of control system. Until computer-implemented controllers became sufficiently powerful and cost-effective, the primary means of administering dynamic spectrum sharing was a trained human operator. Today, automatic control systems can be embedded in relatively low-cost consumer equipment.

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<sup>8</sup> U.S. Proposal for WARC Malaga-Torremolinos, Spain, 1992. Reprinted as Appendix D of U.S. Congress, Office of Technology Assessment, *The 1992 World Administrative Radio Conference: Issues for U.S. International Spectrum Policy—Background Paper*, (Washington, DC: U.S. Government Printing Office, November 1991)

2. Most services where dynamic sharing works are characterized by bursty traffic (such as comes in telephone calls or data traffic) rather than continuous transmissions as are used by broadcast stations.
3. Dynamic sharing works in situations where interference is roughly symmetric. The sharing problems experienced by disparate users in the 902-928 ISM band illustrates how dynamic sharing can fail when interference is not symmetric.
4. Services in which shared channels also enhance communications (e.g., maritime calling channels) are more likely to be able to implement dynamic sharing.
5. Short-range services (wireless LANs, cordless telephones) can benefit from interference control by the landlord. Systems that are characterized by capture<sup>9</sup> and rapid attenuation of signals with distance are well suited to dynamic sharing. We see this in CT2 where interference has the effect of slightly shortening the range that the cordless phone can serve.

## 2. Failures

Where do the benefits of dynamic sharing fail to match its costs? We have the example of the dynamic sharing in the 18261 frequencies. In that case, there were no incentives or opportunity for increased efficiency. In fact, the FCC's rules, in an effort to control congestion, limited the number of customers all carriers combined could serve. In the 902-928 MHz band, the sharing between Teletrac and Part 15 devices failed because of asymmetric interference. In traditional land mobile we have seen the difficulties of moving to newer, more efficient technology.<sup>10</sup> The sharing regime in land mobile has created an interlocking pattern of interference that makes it hard to move to more efficient technologies.

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<sup>9</sup> Capture refers to the ability of the receivers in some radio systems to receive only the strongest signal and to reject the effects of weaker interfering signals.

<sup>10</sup> Cite refarming proceeding order.

Some proposals for dynamic sharing (e.g., Big LEOS, Jackson's 1991 proposal, and Noam's 1995 proposal) have yet to be tested.

### 3. Conclusions

Dynamic sharing is a powerful tool for spectrum management. It offers the opportunity for substantial efficiency gains. Modern technology, especially embedded computer controllers, makes this spectrum management technique much more viable than it was in the past. Dynamic spectrum sharing will be a valuable tool in era of low-cost radios. It works best when the time scale of fluctuations in the use of the radio channel are small relative to license terms—that is it works better with telephone calls than with broadcast signals.