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Governing complex externalities: property rights for sharing radio spectrum

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Abstract
Radio spectrum has become central to technological progress and economic growth. While, command-and-control regulatory institutions of the early twentieth century were considered necessary to counter endemic market failure, recent regulatory reform towards a market regime with flexible licensing creates an interesting environment for examining how complex externalities are managed by private contracting in decentralized systems. We present empirical evidence suggesting that adoption of a more "Coasean" policy regime in radio was followed by far more crowded wireless markets than were formed under rigid administrative structures. This is observed by contrasting pre-cellular mobile phone system outcomes in the U.S. (1946–1978) with the later evolution of cellular networks (1983–2015). The cellular marketplace exhibits exceedingly more complicated network coordination under liberalized property ownership rules. We nest our empirical findings within a conceptual framework derived from theoretical literature on property rights.

Keywords Property rights · Radio-spectrum governance · Complex resource spaces

1 Introduction

Property rights secure claims to the use of resources. These entitlements often enable economic actors to generate more efficient resource reallocations via market mechanisms, substituting for centralized control. However, ownership boundaries may be difficult to define. A prime example is the electromagnetic spectrum–an invisible resource crucial to the effective operation of many valuable services in modern society.

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In this paper we examine the evolution of governance practices for spectrum allocation in the United States. We characterize the history of spectrum regulation as consisting of two parts: a *Tradition Regulation Era* (1946–1978), characterized by command-and-control allocation of spectrum rights by the Federal Communications Commission (FCC) and a *Liberal Regulatory Era* (1983–2015) in which policy makers began implementation of flexible-use spectrum licenses.[1] We examine outcome variables in both regimes to understand the viability of decentralized resource-allocation practices in complex-resource spaces.

Complexity was used as a rationale justifying the placing of all authority over spectrum-governance decisions with the FCC. Yet, we have since observed sophisticated business practices developing in the modern cellular industry, effectively governing spectrum competitively. Vertical integration and customized contracting are extensively used to not only manage interference and coordinate service inputs, but to promote innovation in spectrum-based technologies and services–most notably as seen in the smart-phone ecosystem. We draw from theoretical studies of property rights to explain potential economic mechanisms behind our empirical findings and discuss policy implications.

Our analysis provides a case study of decentralized governance in a complex resource space and emphasizes recognizing the evolution of institutional property rights as a point of intersection between the public-choice and law-and-economics literatures. Our findings complement a growing body of literature emphasizing the importance of avoiding "corner solutions" in policy making. Rayamajhee and Paniagua (2021), argue that the excludability and rivalry of a resource depends on the property rights institution currently implemented. Consequently, different institutions can imply different levels of excludability and rivalry for the same underlying resource. Policy specifying rules-in-use for the resource may adapt these measures to the current economic environment. Our paper highlights how self-interested economic actors operating within an exclusive-rights regime have generated dynamic and evolving resource-sharing agreements without direct intervention by a central regulator.

More broadly, justifications given for regulatory intervention in market economies often posit centralization is necessary to manage *externalities*. Within mainstream economics, externalities are typically associated with missing markets in commercial environments, but scholars have noted difficulties in extending the concept to non-market governance systems such as administrative control (Rayamajhee & Paniagua 2021). Additionally, while missing markets certainly impede the invisible hand from full operation, the forces that generate incomplete market economies often stem from difficulties in defining the intended output distribution of costly economic activies. Such *complex externalities*—also referred to as *novel externalities* (Cowen & Schliesser, 2023)—are notable in that the underlying tensions that generate them will persist even under administrative-allocation systems. In the case of spectrum, whether it be a politician or business manager, someone is still responsible for coordinating the development of sophisticated rule systems in an environment where economic spillover effects are difficult to anticipate, describe, and monitor.

[1] This U.S. liberalization included reform of the rights assignment process, with license auctions introduced by the Federal Communications Commission in 1994. The pronounced characteristic of the policy trend of this era, however, was in the "flexible-use licenses" regulators introduced by relaxing restrictions embedded via administrative law, leaving additional choices as to spectrum deployments—and interference mitigation—to market participants (generally parties holding FCC licenses to supply mobile services). On the introduction of competitive bidding, see Hazlett (1998).

The remainder of the paper is structured as follows. Section 2 discusses the original rationale for centralized spectrum management in the US and the counterargument for decentralized allocation introduced by Ronald Coase in his seminal 1959 and 1960 papers. Section 3 discusses the regime shift to market assignment of flexible spectrum licenses. In Sect. 4, we conduct our comparative empirical analysis. Section 5 discusses how our empirical findings relate to predictions from conceptual models of property rights. Section 6 discusses further applied implications of our findings and concludes.

2 The complexity argument in radio spectrum

In the context of resource allocation, "property rights" are generally entitlements individuals or legal entities have in deciding how an underlying resource is deployed (Segal & Whinston, 2013). In his 1967 paper, Harold Demsetz argues that property rights may form, replacing open access, when technological developments increase the marginal value of resource ownership (Demsetz, 1967). This is particularly true when such changes alter the cost–benefit calculus in defining and enforcing rights (see Anderson & Hill, 1975).

Bundles of property rights take many forms. Two basic approaches are *in rem* and *in personam* (Smith, 2002). *In rem* approaches define boundaries: within that implied space, an owner can exclude unauthorized use and enjoy wide ranging discretion in how the resource is employed shared, transferred, appropriated or consumed. *In personam* approaches grant use rights, where legal institutions specify rules for behavior involving the resource in question. Smith extends Demsetz's conceptual framework by arguing that observed property arrangements can be characterized on a continuum from *exclusive authority* over a defined resource to establishment of *governance rules* which specify how resources should be deployed in (ideally) all states of the economy. Coase's analysis establishes that, if a formal authority can define exclusive rights to resource and there are no bargaining costs, the initial allocation of rights is irrelevant in terms of resource deployments.[2] Resources will frictionlessly flow to highest-valued uses (Coase, 1960; Hazlett, 2009). In this paradigm, *in rem* and *in personam* rules will be equally efficient (and support identical resource use).

In reality, bargaining is not costless, and legal default rules are expected to typically impact efficiency. In the case of spectrum, emissions may be difficult to map and coordinate by contracts, particularly in large-numbers bargaining situations. Damaging spillovers in frequency space may result even when lower-cost solutions are theoretically available. Indeed, in the early days of radio, the Chief Justice of the U.S. Supreme Court William Howard Taft conceded: "I have always dodged this radio question… Interpreting the law on this subject is something like interpreting the law of the occult." (in Coase, 1959, p. 40). This fear that the science would be confounding, and wireless services inherently baffling, was leveraged into a policy conclusion: unless mitigated by centralized control, market failure would be endemic. As summarized by the U.S. Supreme Court:

[2] The identification of this formulation as the "Coase Theorem" did not come from Ronald Coase. "This proposition," wrote George Stigler, "that when there are no transaction costs the assignments of legal rights have no effect on the allocation of resources among economic enterprises…. I christened… the Coase Theorem" (Stigler 1988, p. 77). Coase (1988) found this interpretation problematic, as he bemoaned: "My point of view has not in general commanded assent, nor has my argument, for the most part, been understood" (Coase 1988, p. 1; see also, p. 157).

> Before 1927, the allocation of frequencies was left entirely to the private sector, and the result was chaos. It quickly became apparent that broadcast frequencies constituted a scarce resource whose use could be regulated and rationalized only by the Government. Without government control, the medium would be of little use because of the cacaphony [sic] of competing voices…[3]

Classic works in public-choice theory discuss how collective action may be necessary in situations where large transaction costs impede private-sector bargaining (Buchanan & Tullock, 1962). Furthermore, research on polycentricity and common-pool resource governance highlights the diversity of non-market resource -allocation mechanisms potentially achievable in smaller self-governed communities (Ostrom, 2005). A command-and-control regime is one potential collective-action outcome whereby a trusted authority is granted full discretion over allocating a resource to a group of stakeholders. If this authority has strong incentives to maximize the communal value of the resource—as well as proficiency in monitoring societal outcomes and adapting protocol to changing environments—administrative control could theoretically Pareto dominate market trade in high-transaction-cost environments. Nevertheless, a comprehensive December 1960 survey of U.S. regulatory agencies, performed by Harvard Law School Dean James Landis for the incoming Kennedy Administration (in Coase, 1965, p. 161) declared:

> The Federal Communications Commission presents a somewhat extraordinary spectacle...It seems incapable of policy planning, of disposing within a reasonable period of time the business before it, of fashioning procedures that are effective to deal with its problems.

In his 1959 analysis of radio communications, Coase argued that if the complexity of radio waves made private ownership boundaries difficult to define and enforce in markets, parallel problems would logically exist for regulation.[4] The complexities impacting private contracting also challenge governance structures in a command-and-control regime. In either context, the problem of defining property rights over complex borders, weighing alternative costs of conflict, is confronted (implicitly or explicitly) in organizing production (Coase, 1960). Adopting administrative control over a resource does not eliminate this tension.

Furthermore, as the regulator does not possess special knowledge, and because competitive market mechanisms often reward innovative enterprise, the possibility exists that decentralized choices might improve social welfare. How this plays out, however, depends on the particulars. Property-rights theory suggests that private resource owners operating in a market economy have a variety of organizational strategies to facilitate productive resource sharing, even—or especially—in complex environments. Grossman and Hart (1986) and Hart and Moore (1990) provide a general framework ("GHM framework") that can be applied to study how rights should be allocated to optimally manage externalities. In their model, rules confer residual rights over resource deployment. Resource users can bargain over more efficient allocation schemes after initial rights are granted and uncertainty reduced (transaction costs reduced), but how the surplus from this recontacting is

[3] *Red Lion Broadcasting Co., Inc. v. Federal Communications Commission* 395 U.S. 367 (1969), pp. 375–376.

[4] Coase explicitly critiqued the *Red Lion's* precursor, the Supreme Court decision in *National Broadcasting Co. v. United States* 319 U.S. 190 (1943).

split will depend on parties' initial entitlements. If there are non-contractible actions parties can take to improve total surplus (e.g., efforts to coordinate asset uses, investments in human capital, soft skills, open-ended research activities, etc.), initial control rights should be allocated to promote incentives for supplying positive externalities and mitigating negative ones.

While property-rights scholars have, in recent decades, used Coasean thinking to explore efficiency issues in petroleum deposits, fisheries, land survey methods, common pasture lands, intellectual property, etc., it is less common to see such discussions focus on radio spectrum.[5] Several theories explaining the slow adoption of Coasean thinking in spectrum regulation exist. Some theories suggest regulatory failure in recognizing potential value in pricing spectrum. Other hypotheses posit that the centralized administrative regime may have come about as part of an optimal bargaining solution intended to preserve claims of powerful radio-broadcasting incumbents (Hazlett, 1990). FCC official H.H. Goldin (a critic of Coase, and a defender of the administrative allocation system) wrote in 1965: "Dr. Coase has a clear field with no opposition when he describes the present system of broadcast-regulation, or for that matter any other form of regulation, as less than optimal" (p. 167). But Goldin went on to note Coase's recognition of the rights fragmentation issue and possible "tragedy of the anticommons" (as it came to be called (Heller, 2013)). "When the transfer of rights has to come about as a result of market transactions carried out between large numbers of people or organizations acting jointly, the process of negotiation may be so difficult and time-consuming as to make such transfers a practical impossibility" (Coase, 1959, p. 29). Goldin pounces on this view, which posits a symmetry in the treatment of costs and benefits on competing sides of the policy ledger, as an admission against interest. He writes:

> After the shock of rationally considering the use of the pricing mechanism in frequency allocations, the virtually unanimous view of communications specialists would be that the multiplicity of users both national and international… , the interference characteristics of radio with signals at relatively low energy levels interfering at diverse points many hundreds of miles away (and not confined to national borders) and the hundreds of licensees involved in addition to the many millions of consumers make the pricing mechanism unworkable for frequency allocation. And until Dr. Coase or a friendly ally makes the study he refers to and overturn's the "establishment's" view on this point, I doubt whether Dr. Coase's suggestion will ever get into the mainstream (Goldin, p. 168).

The advantage now available to scholars is that "Coase's suggestion" has gone more than mainstream; the "price system" for allocating spectrum rights has emerged in the mobile marketplace. As per reforms undertaken since the 1970s, rights to control defined radio spaces have been issued to decentralized decision-makers. The policy changes have not been universal and have generally been awarded de facto rather than *de jure*. Nonetheless, important wireless markets are governed far differently today than in 1959.

These institutional changes merit study in the "evolution of property rights" literature not only due to their historic importance in law and economics but due to their assertedly complex nature. In the following sections we describe in more detail the transition from traditional regulation to liberalized licensing in the US spectrum industry. We find

[5] Notable exceptions are found in Merrill & Smith (2001, 2011).

evidence against the common policy assertion that decentralization is categorically prone to market failure in spectrum use. We also discuss how these observations are consistent with modern economic models of resource governance and property rights. Our paper can be seen as synthesizing ideas from the public-choice, law-and-economics, and organizational-economics literatures to provide a comprehensive analytical lens for examining how market governance can perform in relation to administrative-control in complex resource spaces.

3 Spectrum liberalization

Reed Hundt, FCC Chair from 1993 to 97, claimed: "by auctioning spectrum with no rules attached, and preempting all state regulation, we had totally deregulated the wireless industry" (Hundt, 2000, p. 98). The statement contained a dose of hyperbole, as basic spectrum allocation and assignment system was (and is) intact. But the deeper truth in Hundt's statement is correct: a revolutionary change had occurred. For particular bands, especially those of keen interest to emerging cellular telephone networks, the rules had been dramatically altered by 2000. In, contrast, for the most valuable FCC licenses of 1970, issued for television broadcasting, the regulator set narrow, specific terms for:

- the service delivered (video).
- Fixed, not mobile, service.
- The technology mandated (the 1941 NTSC analog format).
- The business model permitted (ad-supported, not subscription-based).
- The location of the transmitter (including height of the antenna).
- The maximum power of emissions.
- The exact frequency space utilized (6 MHz in VHF or UHF).

The frequency space was allocated to the license, not the licensee; stations could be traded, with their FCC licenses included in the transaction (routinely approved as in the "public interest" by the FCC), but the 6 MHz bandwidth could not be devoted to a different wireless service, technology, or business model. The FCC held the power to make such changes, not licensees. The status quo was protected by long delays and high costs for parties requesting changes. While cellular telephone technology was a product of World War II research at Bell Labs, the idea was stalled by the FCC for decades (Table 1). Even in 1970 when the Commission issued an Order in Docket 18,262 setting aside 115 MHz of UHF TV spectrum (as very few UHF stations would need to be re-assigned other channels), it soon reversed course, slashing the cellular deployment to just 40 MHz. And licenses were not yet awarded until 1984–1989 (Hazlett & Michaels, 1993).

Yet, when at long last these first generation (1G) cellular networks were authorized, policy liberalization soon commenced. In 1988, the regulatory technology mandate in cellular licenses was relaxed: licensees were permitted to use the originally mandated Analogy Mobile Phone Service (AMPS) standard or switch to any of the newer, higher capacity, digital systems then emerging.[6] This was done, wrote the Commission, "to provide

[6] AMPS (Advanced Mobile Phone System) was analog cellular phone network standard. Calhoun (1988, 430–432) provides an excellent discussion of the FCC's reform in eliminating the mandated format.

technical freedom in the rules in order to permit the introduction of new technologies" (Calhoun 1988, 430–432). While standard formats may promote economies of scale, market choices tend to internalize such gains against the innovation gains available from competition. The newer perspective proved prescient. A standards rivalry developed, with the spread spectrum techniques used by upstart Qualcomm gaining traction and, eventually, global acceptance.

In 1993 legislation, Congress authorized competitive bidding for most licenses other than broadcasting (Hazlett, 1998). Auctions held since 1994 in the U.S. have raised over $230 billion in winning bids for the U.S. Treasury (current dollars, unadjusted for inflation).[7] The legislation also advanced the FCC push to make licenses used for mobile services generic authorizations, not differentiating between 1 and 2G (or 3G, 4G or 5G); fixed or mobile service; voice, text, data, or video. Services were defined vaguely and broadly as "wireless," not narrowly as "telephone." Licenses largely abandoned the practice of defining how or where networks were constructed, moving from "site licensing" to "geographic licensing." Whereas in the first cellular (1G) permits, each base station (cellular tower) required regulatory approval, Commercial Mobile Radio Services (CMRS) licenses ceded discretion to the licensee as to where to build access points. The most valuable FCC licenses came to feature "flexible use" rights, defining frequency boundaries over which license-holders determine spectrum usage (emission levels, technology, business models, services, network design, applications, content, etc.). These bundles of rights are analogized to private property in radio spectrum.[8]

Hence, we characterize the history of spectrum regulation in the United States as consisting of two separate eras employing different governance regimes:

Tradition Regulation Era 1946–1978. This period saw the development and use of Mobile Telephone Service (MTS), the original "car phones." The product was authorized as a common carrier service by the FCC, and first deployed in St. Louis in 1946. By the following year, the FCC had authorized it in twenty-five U.S. cities. Licenses were issued to three classes of operators: Bell Telephone wireline affiliates, Independent (non-Bell) wireline phone operators, and Radio Common Carriers (RCCs) (firms not having wireline facilities). The licensing structure of this service foreshadowed a pro-competitive shift in regulatory thinking as the RCCs competed with the fixed operators integrating into wireless. Calhoun (1988, p. 35) references the RCCs as "significant, certainly in hindsight" and as the "first intrusion of competition into the telephone world" since the anti-monopoly case against Ma Bell settled in the so-called Kingsbury Commitment of 1913.

[7] The FCC reported: more than $207.5 billion (FCC 2021, 45) in total license auction receipts in April 2021; $22.42 billion (FCC 2022a); in January 2022; and $419.13 million (FCC 2022b) in September 2022. These sum to $230.3 billion (in current dollars, not inflation-adjusted).

[8] The FCC (2002, 35) characterized the emergent spectrum regulatory approach thusly: "A licensing model in which a licensee has exclusive and transferable rights to the use of specified spectrum within a defined geographic area, with flexible use rights that are governed primarily by technical rules to protect spectrum users against interference. Under this model, exclusive rights resemble property rights in spectrum, but this model does not imply or require creation of 'full' private property rights in spectrum." The policy maintains the formal mandate in the 1927 Radio Act: "[T]his Act is intended to regulate all forms of interstate and foreign radio transmissions and communications within the United States… and to provide for the use of such channels, but not for the ownership thereof… for limited periods of time, under licenses granted by Federal authority, and no such license shall be construed to create any right, beyond the terms, conditions, and periods of the license." This explicit denial of private property in spectrum has been circumvented by the FCC in maintaining "public interest" allocation of spectrum by regulators to licenses but then granting the licensees wide discretion in determining the use of the airwaves. See Hazlett (2019).

Table 1 FCC license auction revenues, 1994–2022 ($ Bil. Current)

License type	Total net revenue	Share of total auction revenue
Mobile–low-band	38.4	14.99%
Mobile–mid-band	196.1	76.58%
High (mmW)	10.7	4.18%
All FCC mobile license sales	245.2	
All FCC-reported license auction revenues (FCC, 2021)	230.3	
Plus relocation costs and incentive payments in A107	13.0	
Plus relocation costs and incentive payments in A1002	12.8	
Total winning bids in FCC auctions	256.1	
Share of total FCC auction revenue from mobile licenses		95.75%

Data are from www.fcc.gov. The low-band and mid-band license auctions were sold by the FCC in Auctions 4, 5, 11, 14, 44, 49, 66, 73, 97, 1002, 105, 107, 108, and 110. Auctions 30, 56, 101, 102 and 103 assigned High Band spectrum rights (millimeter wave frequencies). Some auctions omitted given that winning bids were not paid to the Government. Revenues collected by the FCC but then paid out to incumbent licensees were included in revenues in Auctions 103, 107, and 1002

Liberal Regulatory Era 1983–2015.[9] In the cellular telephone era, where the mobile service became known as Commercial Mobile Radio Service (CMRS), the regulator chose to implement a wide range of reforms. CMRS licenses embed:

- Broad, general wireless service definitions.
- Choice of technology.
- Geographic licensing, leaving network design choices to the market.
- Spectrum boundaries defined rather than specific equipment.
- Business models and change of use (for novel applications) delegated to licensees.

Most licenses issued by the FCC are still of the traditional variety, narrowly specifying wireless use rights. However, nearly 96% of all auction revenues collected in winning bids by the FCC, 1994–2022, have been for "flexible-use" licenses that permit fixed and mobile services, defined liberally. The emergence of this resource-ownership rights structure has had a profound impact on market organization, production innovation, and network development in radio-based services. We utilize this social evolution to investigate the issue of complex property rights.

[9] This regime continues through the present. We truncate the historical sample to approximate the timespan of the earlier regulatory episode.

4 MTS v. cellular: comparing technological pathways under distinct regimes

4.1 Analytical approach

Gregory Rosston (2014, 222) notes that, "starting with Coase (1959), economists have argued for market allocation of spectrum." William Melody (1980, 393) offered the counter argument: transactions among spectrum rights owners would result in market failure given the special circumstances in wireless. These two starkly contrasting approaches are useful in appraising the challenges confronting the property rights definition task.

Systematic comparison of property rights regimes is fraught with difficulty. The social, legal, and technological environments are likely to be altered across times or jurisdictions in ways that are not readily discernible in standard multivariate statistical analysis. For instance, in comparing our chosen wireless policy epochs, one major difference occurred in the willingness of the FCC to allocate far more bandwidth to mobile licenses in the more recent period.[10] It is difficult to separate this policy change from other liberalizations of perhaps more immediate interest. Here, however, we attempt to sidestep such issues by tackling a less demanding thesis. The null is:

H0 *Decentralized spectrum access rights are categorically prone to market failure.*

This approach attempts to test the claim made in jurisprudence by the U.S. Supreme Court and by regulatory experts at the FCC. Both warned that embracing Coasean reforms would provoke endemic interference–*market failure*. We evaluate two different regimes, sequential in time, applied to a given wireless application: mobile telephone service. Substantial liberalization of spectrum rights occurred between the two periods. In the first, the authorized radio service was narrowly specified regarding technology, services, and business model; in the second, FCC rules were relaxed such that licenses became progressively more permissive for mobile telephony, delegating spectrum use decisions to licensees. This created de facto private property rights for wireless carriers.

We do not, in any strict sense, compare the regimes and attribute output differences to the net advantages (positive or negative) associated with the policy switch. Rather, we seek to test the null–do the complexities of private property rights, and the decentralized discretion of spectrum owners, overwhelm necessary market coordination?

Our approach borrows from a narrative or case study approach used by Coase (1959) and Oliver Williamson (1976). In critiquing Harold Demsetz's suggested auction of natural monopoly supply rights (Demsetz, 1967), for example, Williamson examined how a specific cable TV franchise actually operated. He was able to isolate arguably general problems of economic coordination associated with franchise bidding. We pursue a parallel strategy, while having the advantage of two rival regimes (and mobile telephone activity spanning the entire U.S. for several decades) to compare and contrast.

[10] The cellular era began with a 40 MHz allocation in the 800 MHz band in 1982; by 2010 the comparable FCC mobile allocation was 547 MHz of low- and mid-band spectrum (FCC 2010, p. 85). The more liberal trend in spectrum allocation is itself a component of the liberalization of interest. But it is not central to our hypothesis test.

4.2 Wireless service performance: MTS and CMRS

The development of mobile phone service across the two eras was markedly distinct. For MTS, the record is summarized in Calhoun (1988, p 10):

> From the promise of those early commercial systems in the late 1940s, the actual deployment of mobile telephone systems proved painfully slow. More than four decades later… [i]n metropolitan Los Angeles, one of the densest traffic centers with more automobiles per capita and many more daily 'driving minutes' than any other large city, the penetration in the mid-1980s is considerably less than 1%!

This pace of technology adoption is difficult to attribute to scientific constraints or a lack of available radio spectrum. FCC policies imposed unnecessary regulatory restrictions on both technological advance and frequency access, failing to accommodate either. Overall, by 1978, there were about 40,000 mobile-phone subscribers supplied by the Bell companies, and perhaps as many as 143,000 including those supplied by independent phone carriers and the radio-common carriers (RCCs). See Table 2

Beyond the pace of subscribership and usage, the adoption of new services appears stymied. Over four decades, MTS remained a voice service, with low bandwidth signaling (similar to paging service) as a byproduct. Technology did not improve much (the major innovation was automatic dialing, allowing subscribers to bypass operator-assisted calls, was adopted) and no significant non-voice applications emerged. The consensus view was that there was nothing new or exciting in the MTS application.

The dramatic growth exhibited in the cellular market stands in stark contrast. Compare subscriber adoption trends displayed in Figs. 1 and 2.

Perhaps far more impressive than the growth in mobile handsets connected to networks, or the high developing utilization of such networks for voice phone calls, was the explosion in innovative services not anticipated in the initial allocations of cellular (CMRS) licenses. Due to the flexible-use policy attached to such permits, a spontaneous growth in texting developed, followed by MMS (multi-media messaging service), and data services. The latter provided a platform for video streaming (e.g., YouTube and Netflix), audio streaming (Spotify, Pandora) conferencing (e.g., Facetime, Skype, and Zoom), gaming, telemedicine, security services, social media (Facebook, Twitter), geolocation and mapping (Mapquest, Waze), and ride-sharing applications (Uber, Lyft), among countless others.

As these innovative software programs are transmitted over wireless networks, they are inherently *interference-creating*, consuming bandwidth that might accommodate rival services. In the flexible-use spectrum environment, these threats of "harmful interference" have not been adjudicated by regulators, as in the traditional approach. Rather, the conflicts are coordinated by carriers, de facto spectrum owners, as spillover costs are internalized. The functional gains to subscribers through the allowance of additional services is balanced against the losses probabilistically imposed on other customers.

Of course, prices are a key rationing tool. Subscribers pay for network access and usage depending on the service: low (perhaps zero) prices for low-bandwidth apps like texting as against premium charges for applications crowding out rival traffic in contentious environments (say, with peak-time voice minute fees in 2G networks, or broadband caps in 5G). Of course, capacity is also constructed, via new cells, upgraded technologies in phones and base stations, and countless other managed fixes to improve the "signal to noise" ratio. This optimization rarely involves adversarial administrative

Table 2 Summary of mobile telephone systems (First Era, 1946–1978)

	Wireline common carriers			RCCs	Total
	Bell	Ind	WL Total		
No. of 2-way channels	23	23	23	21	44
MHz allocated	1.38	1.38	1.38	1.12	2.5
No. of mobile units (Dec. 1977)	44,500	18,200	62,700	~80,000	~143,000
No. of systems (Dec. 1977)	636	716	1351	1375	2726

Channel counts exclude 10 "highway" channels "of limited and declining utility," as well as additional UHF channels shared with television broadcasting "since there has not been time for significant usage to build up" (Young, 1979, p. 6). RCC subscribership is estimated from data in 1976 and previously, leading to the approximations shown. (*Id.*) *Source* Young 1979, p. 6 (Table II)

proceedings, even when conflicts spill over spectrum boundaries to involve multiple operators (Rath, 2011). Instead, less costly methods of interference avoidance are embedded into business models and quality of service dimensions. Competition among carriers to enlist customers provides feedback, governing choices.

With traditional rules in place during 1947–1978, the "Car Phone" service was static, and additional products were not created. This avoided "interference" in one sense, but sacrificed the gains from innovation, increasing "interference" in another.

The more liberal regime, evolving 1984–2015, produced a strikingly different outcome. Under CMRS rules, carriers exercised effective control over spectrum use. They used this power to adopt new technologies, services, applications, and business models. A dramatic expansion in the mobile product menu occurred, as the fundamental service morphed from *voice* to the *bundle*: voice, messaging, data, pictures and video. See the trend in Fig. 3.

The market allocation of radio spectrum occurring during the liberalization period is noteworthy and can be explained in a simple historical dichotomy.[11] In 1934, inventor and Columbia professor of physics Edwin Howard Armstrong sought to deploy his new FM ("frequency modulation") technology, a substantial advance over the AM ("amplitude modulation") radios then serving the broadcasting market. Given the lack of transferable rights and change of use, his path was solely through the regulatory system.

In 1939, the FCC granted a limited number of FM licenses, enabling the construction and operation of a network of stations in the Northeast U.S. While mobilization for World War II soon halted consumer goods production, about 400,000 receivers had been sold and received rave reviews during the war years. A predicted boom in sales was deterred in the post-war period, however, as the FCC launched a 1945 proceeding to arbitrarily shift the entire FM spectrum allocation, which had been assigned 42–50 MHz, to a new location at 88 to 108 MHz. The reallocation made existing receivers obsolete, while the higher band authorized automatically subjected the technology to a transitional delay, as FM radio technology had to be redesigned. The abrupt decommissioning proved devastating for the upstart. When the FM rival systems were at last allowed to fully compete in the 1960s, their audiences—attracted to FM "hi-fidelity" quality—soon overtook those of incumbent AM stations. The innovation had, however, been suppressed for about a quarter-century.

[11] This discussion tracks Hazlett (2017, 62–69, 176–177, 223–228).

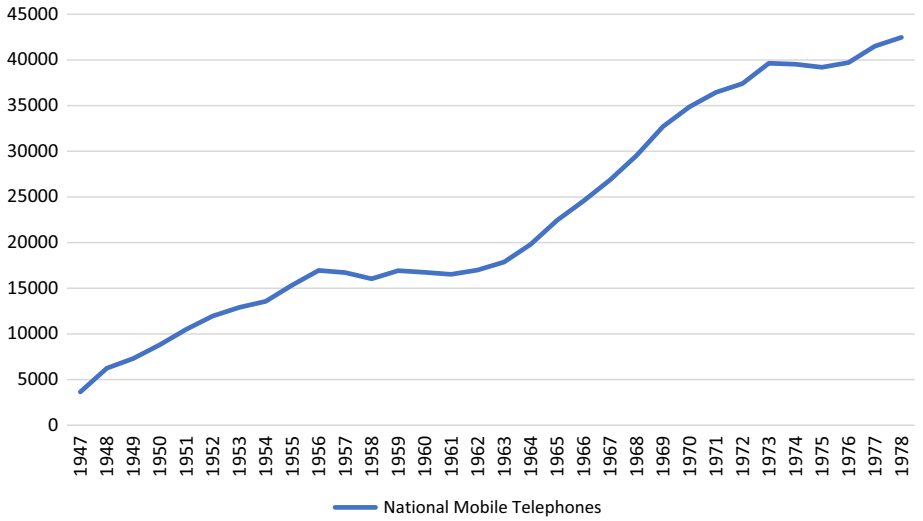

Fig. 1 Mobile telephone subscriber units, 1947–1978. *Source* https://www.fcc.gov/general/statistics-communications-common-carriers (accessed August 12, 2022, "Company Telephones By Type of Switchboard," Federal Communications Commission's Statistics of Common Carriers, Years 1946 to 1983. In 1968, ell MTS accounted for "about 50%" of total MTS subscribers (Hardman 1982, p. 386), while in 1977 Bell MTS accounted for approximately 31% of total MTS subs (Table I)

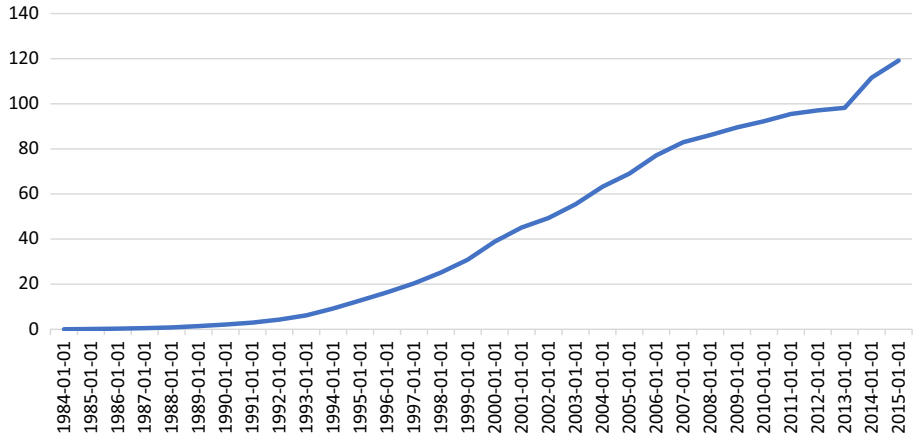

Fig. 2 U.S. Cellular subscriptions, 1984–2015 (mil.)

Like an FM radio, an Apple iPhone relies on a key complement: access to radio waves. While Armstrong faced political and economic barriers that can generously be described as a *high transaction cost environment*,[12] Apple faced a relatively low-friction spectrum market. The market distribution of exclusive, flexible-use licenses allowed the firm to contract

[12] Armstrong, distraught over the suppression of his life's work, committed suicide in 1954, age 63.

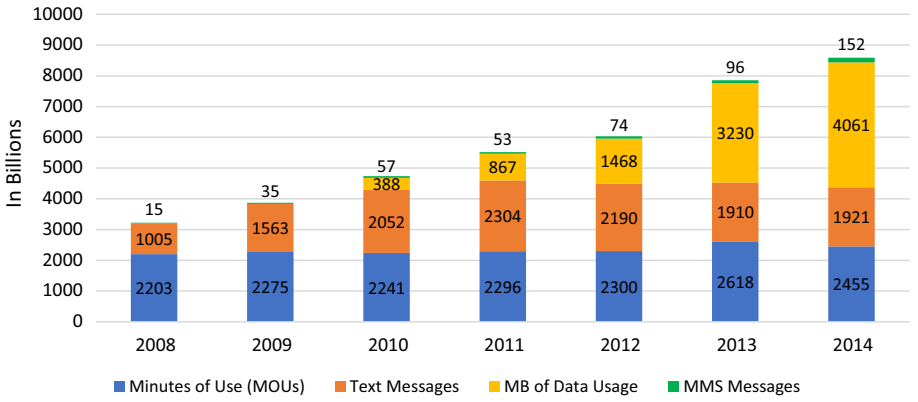

Fig. 3 Voice minutes, text/multi-media messages, and data via mobile, 2008–14 (*Source* CTIA (2015), p. 144 (Chart 32).)

for band access. With mobile carriers holding frequency rights, these parties assume control over network access via radio interfaces, both by end users (who pay subscription fees), and wireless device makers (who supply inputs to networks and individual customers). Indeed, each mobile carrier tests and approves (or rejects) such devices for use in their network, operating as a sort of mini-FCC—policing protocols, matching technologies, and directing traffic. This authority extends to content, services, and software applications by third-party vendors.

To launch the iPhone, Apple needed permission, but not from regulators. Rather, mobile operators held the key spectrum property rights. For its launch in the U.S. in June 2007, it obtained an exclusive agreement with AT&T. Apple did not *pay for* spectrum access but was *paid by* AT&T for making the iPhone available on the AT&T mobile network.[13] The exclusivity arrangement soon ended, and agreements for iPhone access were consummated with all other U.S. carriers. Similarly, Apple reached agreements with hundreds of mobile networks around the world. The introduction of flexible-use licenses, which had spread to regulatory regimes globally, delegated interference mitigation decisions to market competitors. This key policy innovation supported the emergence of market coordination for the product innovator.

As the iPhone rolled out, it was a distinctly interference-creating disruption. AT&T immediately discovered iPhone users to be "spectrum hogs," spending dramatically more time online and downloading data far more intensely than rival phone users. The network invested aggressively to upgrade its 3G system, priced or otherwise rationed high-data users, policed applications to limit spillovers between users, and off-loaded wireless traffic to local fixed networks via Wi-Fi. But the "Smartphone Revolution" was on. Apple displaced

[13] Steven Chueng (1973) studied beekeeping, where inputs (bees) produce marginal products across two markets. Beekeepers in some cases were paid by farmers (orchard owners) to locate hives nearby (inducing additional pollination), while beekeepers sometimes paid farmers for placing hives in locations where honey production (captured by the beekeeper) was relatively productive. The analogy to the Apple-carrier contract is that the iPhone was generally so valuable to the mobile carrier that Apple was paid a premium to "locate" its devices there, despite the fact the carrier was also supplying a valuable input to Apple's phone customers (radio spectrum).

Nokia's Symbian, then the leading smartphone software platform, and vanquished the early smartphone innovator, RIM Blackberry. This bruising success triggered yet additional challenge, however, as Apple's 2007 iPhone innovation was then countered by Google's 2008 entry via its Android product. Google, dominant in computer search, sponsored a rival competitive coalition by developing Android's mobile operating system and licensing it without charge to manufacturers of phones, tablets, computers and other devices. The highly profitable foray allowed Google to dramatically extend the use of its search tool.

Even more pronounced was the creation of verticals via the Apple App Store and Google Play. Ecosystems were created, using access to flexible-use spectrum, to transmit a burgeoning innovation: mobile apps. The Apple App Store was launched in 2008 and by 2014 hosted some 75 billion software downloads for smartphone use.[14] The competing Google Play store, offering downloads for Android phones performed similarly.[15] Due to the utility of the wide-ranging software programs, smartphones replaced cellphones, tablets (following smartphones) connected to data networks, smart watches were launched and the ensuing niche—"wearables"—augmented the wireless product array.

Each of these millions of apps and thousands of devices, drew bits from wireless networks, "interfering" with existing connections and threatening to harm incumbent users. The truncated spectrum use rights the FCC traditionally issued were a response to this threat; the proffered remedy to anticipated market failure. The FCC had addressed potential tragedy by protecting existing wireless activities via restrictions on entry, and by imposing technological uniformity and centralized discretion. But the systemic over-protection of the status quo was, in fact, the more serious problem, as revealed by the experience gleaned in the wake of this regime shift. A vast increase in data usage supplied by mobile carriers was seen (Fig. 4).

In 1967 (the last year for which the FCC posts data on MTS revenues) there were $16 million in subscription revenues. U.S. cellular industry subscription revenues in 2004 (after 20 years from earliest deployments) totaled $102 billion.[16] The 6300% increase in nominal revenues is not determinative as to the policy margin we seek to understand here; what is relevant, though, is that the expansion of the wireless market in the latter period was achieved under rules in which the conflicts for bandwidth were primarily adjudicated by licensees in the private sector, exercising control over "flexible use" spectrum rights.

This dramatic expansion in wireless adoption was itself associated with unprecedented innovation in the "App Economy." These new vertical services emerged under the liberal spectrum allocation regime and would predictably have been deterred or blocked altogether by the restrictive rules previously in place.[17] The regulatory reforms enabling this new trend were explicitly undertaken to enable competitive developments, even as the precise (or even approximate) nature of the "app economy" was not forecast by regulators or, for that matter, even the platform organizers or software developers who later collaborated to bring the new markets to fruition. The emergence of a mass market in mobile services, with subscriptions climbing to in excess of one hundred percent of population,[18] tends to

[14] Sarah Perez, *The App Store Now Has 1.2 Million Apps*, *TechCrunch* (June 2, 2014).

[15] Mansoor Iqbal, *App Download Data (2022), Business of Apps* (Aug. 31, 2022).

[16] *Service revenue of the U.S. mobile wireless industry 1985–2021,* Statista (Nov 10, 2022).

[17] FCC Chair William Kennard demonstrated the general logic when speaking at an agency hearing, in May 2000, about relaxing rules for secondary market transactions: "I'm very excited about this prospect because, to me, it imports another powerful market-based tool to spectrum management and gets us out of this "mother-may-I" approach to managing the spectrum." FCC (2000, 10).

[18] "In terms of total mobile phone usage, Comscore found that 234 million Americans older than the age of 12 used a mobile phone. That's about as close to universal adoption as you can get." *Smartphone Penetration Reaches 100 Million*, Tech Guru Daily (Mar. 8, 2012).

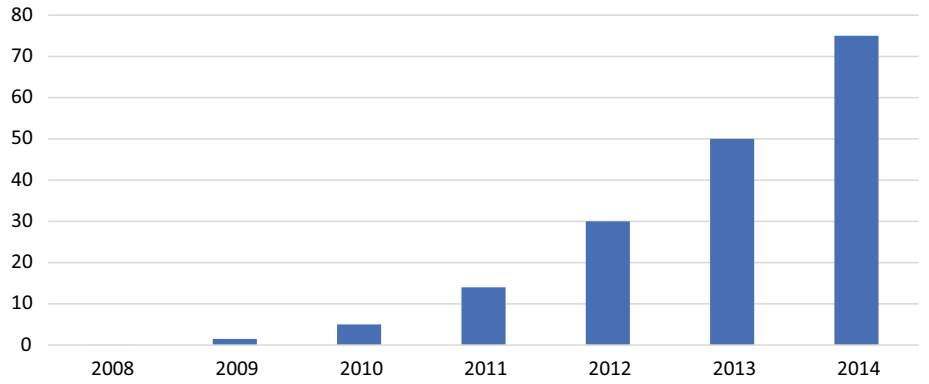

Fig. 4 Cumulative iPhone apps downloaded (Bil.). *Source Statista* (July 21, 2014). Each annual figure from July (or closest month to July given). 2008 value (not visible) equals 0.01

reject the Null which asserts endemic market failure in interference coordination under a liberal regime. Yet the deployment of ubiquitous wireless mobile two-way devices (categorically more challenging to organize than fixed broadcasting services in radio or television)[19] and the creation of innovative networks, platforms, and ecosystems dense with new applications are observed to evolve, ostensibly unimpaired by "chaos."

Our null hypothesis was sketched out by H.H. Goldin, who critiqued Coase's proposal for property rights in 1965. Yet, Coase's basic suggestion was enacted. The FCC adopted reforms that have endowed many licensees with de facto property rights in radio spectrum. We here examine how this progression has produced improved understanding of property rules. We observe that delegating spectrum use decisions to decentralized spectrum owners is not categorically inefficient.

5 Organizational and technological approaches to internalizing externalities

Comparative analysis of mobile services provided in the MTS and CMRS regimes leads us to reject the assertion that decentralization of spectrum allocation via market mechanisms inevitably generates "etheric bedlam." Here, we consider how coordination methods established in the CMRS ecosystem relate to insights derived from theoretical studies of property-rights institutions.

As transmitters and receivers interpret radio signals across a range of frequencies, value is increasing with additional bandwidth for any given system. But consuming marginal channels in radio space results in "interference," reducing opportunities for others. Some

[19] The "market failure" claims made for spectrum markets by Goldin, Melody, the Supreme Court, and elsewhere were based on assessment of broadcasting; cellular did not launch in the U.S. until 1984. By way of comparison, the radio market of 1980 featured a little over *9000 stations nationwide* (AM and FM). In 2011, there were *2289 TV stations* assigned VHF and UHF channels. Coordinating interference among this number of fixed, one-way transmitters would appear orders of magnitude less complicated, as a technical matter, compared to policing conflicts among over 100 million mobile phone users (see Fig. 2) sending and receiving content wirelessly while stationary or moving at 70 miles per hour.

rationing occurs with this scarcity,[20] whether by regulatory edict, market contracts, or some combination. Network operators augment spectrum rights using (or developing) available technologies, optimizing applications to conserve bandwidth, or acquiring additional frequency rights (say, at auction). Each constitutes an attempt to internalize gains from implemented efficiencies.

Empirical as well as theoretical literature on firm boundaries have studied how vertical integration may contribute to resource-coordination solutions in supply networks (e.g., Monteverde & Teece, 1982; Williamson, 1975). Leveraging asset complementarities by coordinating resource use becomes a component of profit-maximization in large, integrated firms. Joint ownership, as in vertical integration, may mitigate opportunism, free riding, and other coordination problems.

An interesting feature of the mobile ecosystem is vertical integration between service carriers (who operate wireless base stations and backhaul links connecting traffic to the public switched network[21]) and spectrum licensees. An alternative structure might feature an ecosystem in which specialized "spectrum aggregators" contract with carriers.[22] The integrated structure we observe is consistent with theories of economic organization in the presence of transaction costs.

Further, there are many complementary services provided to mobile subscribers that are supplied directly by third-party vendors. These include app developers (of, say, Mapquest, Spotify or Kindle), content creators (e.g., Netflix or Angry Birds) or media platforms featuring user-generated content (YouTube or Facebook). These products drive demand for mobile-phone network subscriptions, and often generate revenues in ad sales or purchases in the ancillary applications market, yet consume bandwidth. Mobile carriers, directly and through the technologies they deploy in their networks, establish protocols for such services. This is an attempt to optimize the social use of spectrum, a common-pool resource shared by subscribers. The birth of the "wireless web," often credited to the launch (in Japan) of NTT DoCoMo's iMode feature in 1999, was concocted in a strongly vertically-integrated environment in which the phone carrier established tight rules for applications, restricting consumption of bandwidth and hence sharing spectrum nicely. (This was in a narrowband environment where the constraints of bandwidth scarcity were presumably much tighter than in the broadband networks to follow.) The business model was described as a "walled garden," given the control exercised by the network operator, but i-Mode

[20] There is currently no scarcity of radio frequency space for terrestrial broadcasting on Mars. Open Access works perfectly well there today as a regime and it would make little sense to expend any substantial resources to attach State, Common, or Private Property Rights.

[21] This is the somewhat antiquated name for interconnections between operators (as when a T-Mobile subscriber calls an AT&T subscriber). It now includes data transmissions, of course, that flow over the Internet and which may avoid the "public switched network" in part or in whole.

[22] Indeed, while mobile network operators T-Mobile, Verizon and AT&T generally do own the FCC licenses granting the spectrum rights their subscribers utilize, each buys tower space from firms such as Crown Castle or American Tower. These suppliers host (and hoist) base stations on elevated platforms, improving cellular coverage. They exploit scale economies, supporting multiple (competing) carrier infrastructure in the same, advantageously located, platform. American Tower *describes* its company as an "operator and developer of wireless and broadcast communications real estate." Across 43,000 properties in the U.S. and 181,000 internationally, it generates revenue by "leasing space on wireless and broadcast towers" and supplying "antenna systems… that speed network deployment." While wireless networks used to build, own, and maintain such facilities internally, they have decidedly shifted in favor of contracting out this element of network provision. See, e.g., Sarah Thomas, *Verizon Sells Towers & Wireline Assets for $15B*, Light Reading (Feb. 5, 2015).

proved extremely popular with both app developers and phone subscribers (Hazlett & Wright, 2012, pp. 791–792).

It is also appropriate to view the network operator as a *platform sponsor* (Teece, 1986) who markets a complex *bundle of services* (e.g., voice, messaging, internet access, camera, etc.). This commodity requires a variety of inputs to produce, two of which are base-stations and spectrum licenses. As these two inputs are closely co-specialized, joint ownership is intuitive (Klein et al., 1978). The network operator internalizes externalities associated with coordination across spectrum rights and base-station equipment, which is then reflected in its investment decisions and pricing rules.

As shown in Fig. 5, which displays a popular graphical summary of the "mobile ecosystem," numerous additional inputs are still required for network operators (carriers) to construct their service bundle. Protocols are generated to match those who demand spectrum with appropriate access. In a command-control regime, these governance rules would be more constrained by law, more often directly designed and implemented by a central administrator. The CMRS regime, in contrast, allows greater flexibility for governance rules to be crafted by autonomous entities, sponsored by the platform's residual claimant. There are costs in executing spectrum-sharing agreements, and mechanisms used to coordinate disparate plans from the parties involved tend to be selected for their relatives effectiveness. Those who participate in this bargaining process receive benefit for their efforts. Within the context of property-rights theory, market trade and customized contracting are decentralized mechanisms for forming complex governance rules—and then re-forming such rules with market feedback. That is seen in modern cellular communications networks, which host dense economic activity using common resources where "interference" is endemic. In this process, firms discover and implement business models from experiments made possible, in large part, by the relative flexibility of resource rights.

Lastly, network operators recognize market dynamics. Valuable spectrum services change over time, particularly in response to innovations in technologies or entrepreneurial discovery. Incentives for third-party innovators drive investment in developing technologies and services that complement spectrum resources, increasing demand for wireless service. In the context of the GHM framework, customized contracting between separate firms—as opposed to integration—preserves claims to bargaining surpluses. Consequently, tailored agreements protect specific, unsalvageable investments, even when returns are not directly observable or verifiable, or option values impossible to specify. In the case of spectrum, we observe technology and app developers striking contractual arrangements with carriers, such as Apple's contract with AT&T for iPhone radio access, solidifying claims to substantial profit streams, enhancing the value of the shared ecosystem.

6 Lessons learned from coase's critique

Command-and-control regimes are not without their advantages. In some instances, coercive reassignments undercut holdouts, moving markets toward efficient equilibria. Finding the right mix of government rules and market incentives is the challenge (Winston, 2021). In radio spectrum, it is notable that considerable progress has been made in this regard.

The innovative networks, services, and products that flowed to market during the Liberal Regulatory Era were not notable in *reducing* observed interference but in *increasing* it. Indeed, it is in vastly more crowded wireless markets that society enjoys the Smartphone

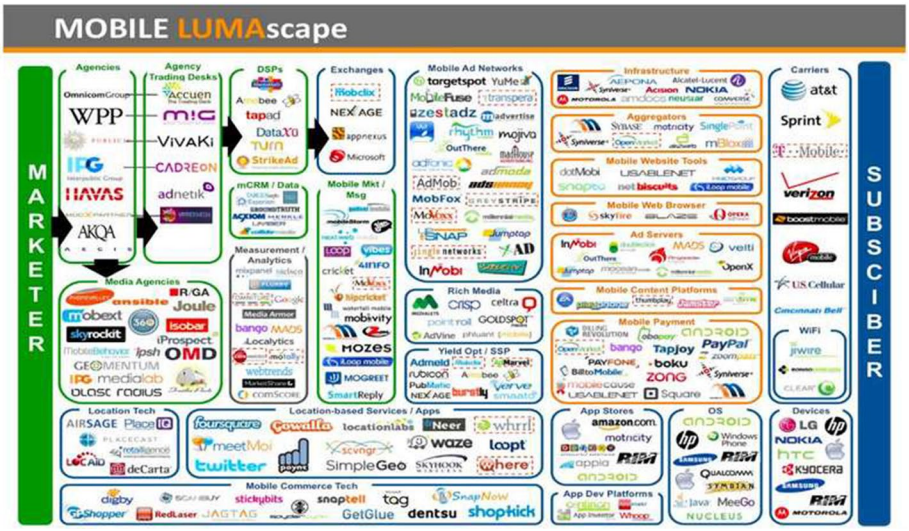

Fig. 5 High Level summary of the mobile ecosystem

Revolution. Recent developments in wireless illustrate Demsetz's base case for private property rights, facilitating investments in productive enterprises given the lower transaction costs associated with capturing benefits. The regime shift to flexible-use spectrum rights proved promising to Coase and then effective in supporting the "wireless craze" (Hazlett, 2001). Regulators have themselves noted the sea change in innovation.

It is important to reemphasize however, that the current liberalized spectrum regime in the United States remains monocentric: default ownership of spectrum-access rights ultimately lies with the government agencies such as the FCC. For example, the FCC could, in theory, alter or discontinue the policy liberalization at their discretion. This suggests potential value in considering a wider array of additional governance options varying in how default spectrum rights are allocated across private and public entities. It also suggests a need for a deeper understanding of the role regulators should play in decentralized ownership regimes.

The evolution of governance practices in U.S. spectrum regulation highlights how difficulties in defining property rights in complex resource spaces may be dealt with. From a policy perspective, Coase's insights point the way to rational governance: the goal should be to maximize the net social value of spectrum-based services. This not only requires addressing property-boundary issues through an economic lens, but also considers the merits of delegating decision-making to decentralized actors. This may facilitate spectrum-sharing rules far more subtle and socially advantageous than attained via administrative controls. In radio spectrum, it appears to have done just that.

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