Time-Limited Leases in Radio Systems

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ABSTRACT

A time-limited lease is a set of rights that expires after a specified duration. We analyze ways to use leases to facilitate innovation in radio devices and wireless communication. In our vision, manufacturers include in their devices a simple, secure subsystem that contains a clock and disables specific transmit capabilities if no extension message is received by the end of the lease period. When devices provide this support, regulators may use certification leases rather than permanent grants to accelerate deployment of innovative radios. Spectrum rights holders may use leases to reduce risk in secondary spectrum market transactions. Firms collaborating in innovative wireless service business models can better retain control of their respective rights. We examine both the technical and policy issues associated with leases.

INTRODUCTION

Advanced radio system designs such as cognitive radio, dynamic spectrum access, and secondary spectrum trading offer significant potential benefits, ranging from better spectrum efficiency and communication system performance to improved competition and innovation in wireless services. But these approaches also create new risks for many stakeholders, including regulators, spectrum rights holders, and system operators [2–5].

Time-limited leases can help mitigate these risks and thereby promote deployment of innovative radios and services. Leases are conceptually simple. They behave just like the *time out* programmed into trial versions of software packages. In this case, the time limit is built into a radio device. If the time limit is reached and no extension message is received, the radio reduces its behavior as required or potentially halts transmission entirely.

Time-limited leases facilitate radio innovation by enabling various stakeholders to better manage risk. A regulator, faced with a device too complex to test thoroughly, can certify it for sale and operation knowing that it is easy to recall if it misbehaves in the field. A spectrum rights holder, faced with an offer for secondary access to their licensed spectrum, can enter into the contract knowing that the secondary user will cease operation at the end of the specified period.

Leases are extended by delivering a *certificate* to a device. A certificate is just a string of bits that encodes what operations are permitted (e.g., transmission at a specified power in a specified band) and provides a time limit. In most applications, certificates will be encrypted and/or cryptographically signed to assure that only the responsible authority is able to extend the lease. We anticipate useful certificate duration ranging between hours and months depending on the application.

TECHNICAL BENEFITS OF LEASES

Leases are a predictable, secure, and decentralized mechanism for limiting the potential harm to a stakeholder's interests. At the system level, leases are simpler to implement and more robust than a *kill button*. A kill button is a mechanism that enables a stakeholder to proactively shut down a group of radios or some of their behavior modes. Kill buttons are feasible to implement in centralized systems; but in decentralized systems, it is difficult to guarantee that the kill message reaches all the devices in a timely fashion. With leases, devices automatically halt their behavior if they do not receive the approval to continue operating.

At the device level, leases are simple to implement. All that is required is a reliable clock and a protected execution environment for software that checks transmitter settings against a stored lease table. This simplicity is a key advantage of the approach. It means that lease support can be provided in radio devices at minimal cost. Just as important, the simplicity of lease support means that the lease subsystem can be validated to a high level of assurance. This gives confidence to various stakeholders that leases will be processed correctly, which is essential if the stakeholders rely on leases to manage their risk.

Lease support is not appropriate for all devices. Low-end devices like sensors may not be able to support the required functions, while centrally controlled devices like cellular base stations can easily provide kill button functionality that makes the leases unnecessary. However, time-limited leases are appropriate for a wide range of devices and place only minimal constraints on radio system design.

This article is adapted from a longer DYSPAN 2007 conference paper [1]. Refer to that paper for a more in-depth discussion of many of the topics introduced here.

Policy Benefits of Leases

By limiting the potential harm to a stakeholder's interests, leases enable shifting from today's dominantly *ex ante* enforcement approach to one more balanced between *ex ante* and *ex post* enforcement of those interests. This facilitates innovations where there is a high-perceived risk due to novelty or complexity.

Leases can be an effective complement to more traditional regulatory and contractual mechanisms. In most cases, leases will be an optional mechanism. A manufacturer can choose to apply for time-limited certification for some devices and traditional certification for others, depending on which decision makes the most economic sense. A secondary spectrum user can approach a primary rights holder with a contract that is technically enforced by leases or with one that is not.

In cases where leases are used, they can be combined effectively with more traditional mechanisms. In the regulatory certification application, the simpler operating modes of a device could be given traditional permanent certification while the more sophisticated modes such as dynamic spectrum access are limited by leases. If the lease expires, the radio would not halt entirely but instead would be limited to its simpler operating modes.

Applications of Leases

Device Certification

Device certification is the process where a radio is shown to comply with interference and safety regulations before sale. Currently, devices are validated to a high level of assurance, then receive a permanent *certification grant* allowing ongoing sale and operation. Leases could be used to enable a new category of certification, that is, limited-duration *certification leases*. Certification leases are extended periodically by the regulator if the device operates safely in the field. The presence of a trusted lease subsystem in the radio gives regulators high confidence that the device will be upgraded or cease operating, if necessary, in a timely fashion.

Certification leases are a valuable policy option. They can help overcome three barriers to innovation created by the current device certification approach.

First, today's innovative radio systems are dramatically more complex than earlier legacy radios. Even a low-end device can easily have enough states and transitions to make full validation prohibitively expensive. Certification leases limit the harm caused by devices if design mistakes are not detected during testing, reducing the required level of assurance and hence the cost of certification.

Second, innovative radio systems seek to exploit novel spectrum access mechanisms such as listen-before-talk or interference temperature-based access. The impact of behaviors like these on other radio systems is difficult to analyze in advance of large-scale deployment, and the design assumptions used to develop the spectrum access mechanisms may become invalid as the external world evolves. Under the current certification approach, such problems mean that only extremely conservative radio designs can be used. Certification leases limit the potential harm that can come from these problems. Hence leases enable certification of more aggressive radio designs that achieve higher spectral efficiency.

Finally, as market and technology cycles continue to accelerate, regulations must evolve more quickly to keep pace. However, permanent certification of inflexible devices makes this difficult. Certification leases give regulators the ability to plan for change by assuring that fielded devices respect an established sunset clause in a given band. Certification leases are especially valuable for devices that may be deployed in a viral or decentralized manner, where there is no identifiable operator to take responsibility for enforcing the sunset date.

Certification leases have two major limitations. First, they can be used to reduce device certification barriers only when misbehavior for a bounded period of time is acceptable. There are types of harm where any period of misbehavior is unacceptable, such as interference with life-critical communications. High-assurance validation to rule out these types of harm is required even when lighter-weight certification enabled by leases is used for the more complex operating modes of a device.

Second, leases will limit harm only if interference that occurs in the field can be traced back to the devices that caused it. Interference resulting from advanced radio devices is likely to be transient and may be a cumulative effect of transmissions by many devices from several manufacturers. Both these effects make analyzing it difficult and expensive. Better interference analysis approaches must be developed to go along with certification leases.

Secondary Spectrum Markets

Secondary spectrum markets enable trading or sharing of spectrum access rights between primary rights holders, who hold licenses from the regulatory authority and secondary users. Secondary markets may arise in a variety of contexts and forms, including non-cooperative or cooperative trading of primary or secondary access rights [6].

Secondary markets have been established within the last decade in several countries. However, they have remained largely moribund. There are multiple reasons for this, including high transaction costs and technical challenges. One apparent barrier is the risk perceived by the primary rights holder that the secondary user will violate the terms of the transaction.

Time-limited lease support in radio devices can be used to reduce the risk of some violations. For this purpose, the devices are configured to accept only certificates authorized by the primary rights holder. This assures that the secondary user ceases operating in the specified band at the agreed end of the lease, never transmits beyond power level limits, and only transmits at approved times of day. The secondary user also can be limited to specified geographic areas if the lease subsystem includes GPS (global positioning systems) or some other location sensing mechanism.

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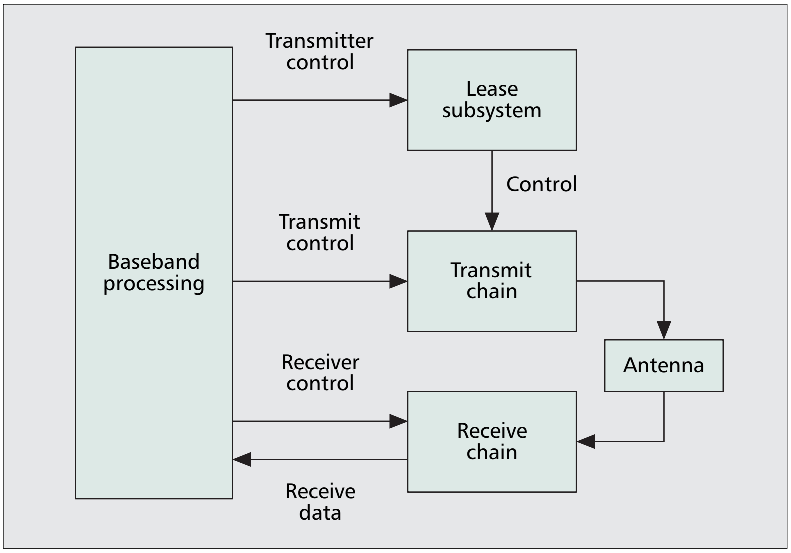


■ **Figure 1.** *Architecture of a radio with lease support. The transmit chain contains the frequency up-conversion, signal amplifiers, and filter hardware. Control of the transmit chain passes through the lease subsystem, which checks that each new configuration is valid.*

By reducing risk and protecting the interests of primary rights holders, leases lower the barrier to secondary spectrum transactions and hence facilitate growth toward better spectrum allocation and higher overall economic efficiency.

Novel Business Models

Time-limited lease functionality can be exploited to enable novel services or alternative ways of deploying existing services, such as the following.

- *Self-enforcing distributed contracts*: the lease table in the device may have multiple entries referring to the same band. If any one of them expires, the lease subsystem shuts off access to that band. Assuming different signatures are required to update the different entries, multiple collaborating businesses can each have partial or full veto power over the operation of the radio. By enabling lower-cost options for distributed contract enforcement, leases may be especially well suited to support innovative business models that exploit unlicensed spectrum or viral networks.
- *Cooperative radio meshes*: lease renewal can be used to enforce cooperation in a distributed radio network. For example, nodes can be rewarded or penalized by receiving greater or lesser transmission rights based on their contribution to the overall network (e.g., retransmission of other node packets).
- *Disposable radios*: radios with time-limited, non-renewable leases would have a finite and pre-determined life. For example, this enables the use of extremely aggressive spectrum access etiquettes in appropriate contexts. One example is a radio attached to a fire extinguisher that activates only when the extinguisher is operated.
- *Pre-paid radio services*: pre-paid cellular services already exploit time-limited lease behavior. If lease support were built into a range of devices, this business model could be extended to other contexts, including ones where entities with an incentive to acquire free service have the capability of modifying the radio's software.

Although it is not clear which, if any, of these approaches will lead to successful businesses, leases promote experimentation by the market and expand the range of feasible business models.

Implementing Leases in a Radio

Architecture of the Lease Subsystem

The lease subsystem must be the only part of the radio that directly controls the RF-transmit (radio frequency) chain devices. This control enables it to prevent unauthorized transmissions.

The lease subsystem also must be separated from the main part of the radio, which we loosely call the baseband processing subsystem. Separation means that the lease subsystem has its own processing and storage resources and that it is connected to the baseband subsystem by a constrained interface. This enables validating the lease-related functions of the device to a very high level of confidence at a reasonable cost.

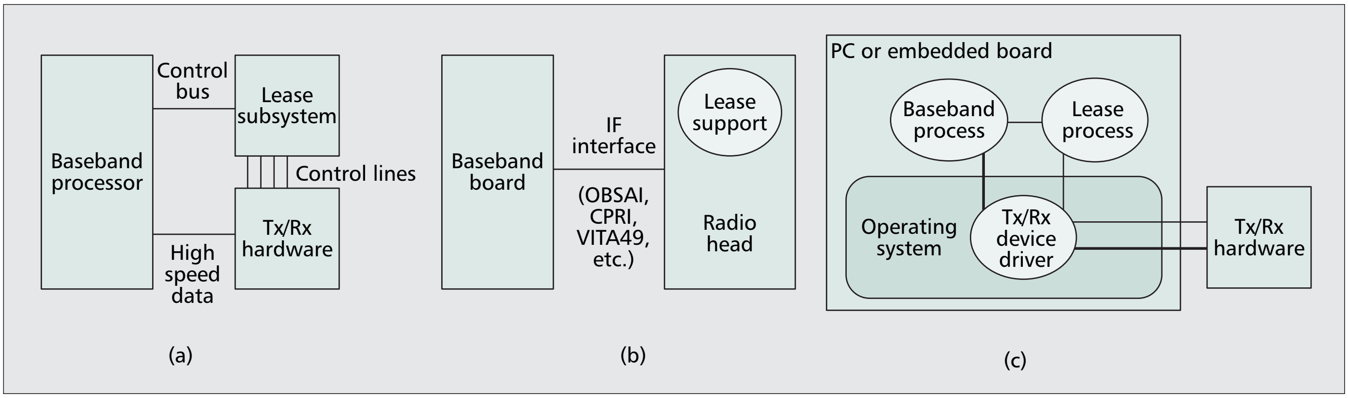
In most radios there is a microcontroller or subsystem that translates between the multiplexed control bus of the device and the individual control lines of the radio RF analog devices such as amplifiers, oscillators, or filters. This is one cost-effective place to add lease support to the radio (Fig. 1). As it is the only component with direct control of the transmit chain, a lease subsystem in this location can check any attempt to tune to a different frequency or change transmit power, bandwidth, or other parameters.

The lease subsystem can be implemented in multiple ways (Fig. 2). In (a), the subsystem consists of a set of hardware components on the board of a highly integrated mobile device. In (b), the subsystem functions are provided by a radio head that is linked to the baseband board via a standard interface. In (c), the lease subsystem functions are performed by an independent software process. The process boundaries of a commodity operating system (OS), such as Windows XP or Linux, provide sufficient isolation for the lease process in some applications. In other applications, a more secure OS would be required.

If the lease subsystem is implemented as separate hardware, a processor, a clock, and some local storage (Fig. 3) is required. The hardware required is only a small increment beyond the microcontroller used at this place in current radios, so the cost increase is trivial for all but the most cost-sensitive high-volume devices. In cases where it is valuable to limit leases by location, in addition to time, the radio location sensor is moved into the lease subsystem, again with small cost impact.

Behavior of the Lease Subsystem

When the lease subsystem receives a request for a new transmit-chain setting, it checks that the configuration is acceptable before acting on the request. There are many ways to implement this check, which is called *transmit validation*. Logi-



■ **Figure 2.** *Potential implementations of the lease architecture: a) integrated mobile device; b) modular infrastructure device; c) PC-based software radio.*

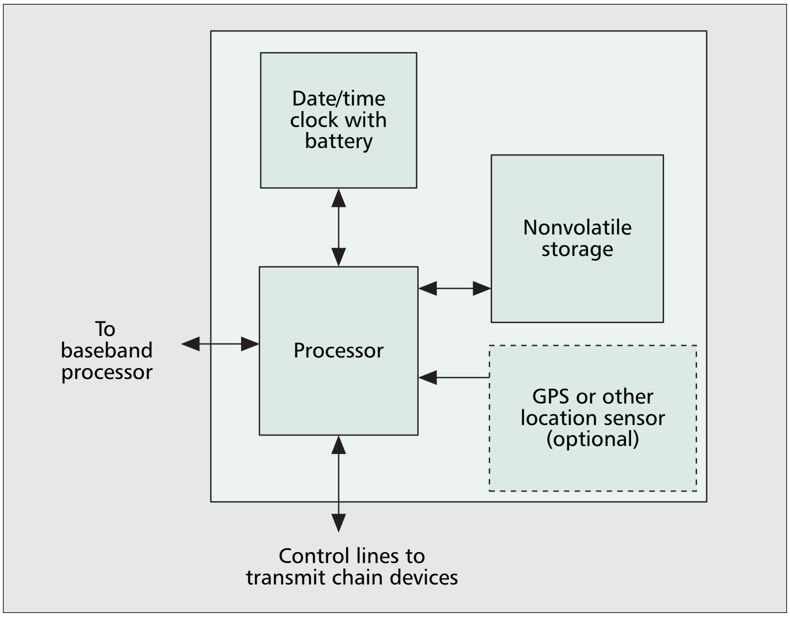
cally, it can be considered to be a lookup in a table with information of the type shown in Table 1. In practice, more sophisticated representation and query processing mechanisms can be used. For example, multiple entries may cover the same band, either with OR semantics or AND semantics, depending on the application.

During periods of stable transmit chain settings, the lease subsystem must perform work only when a lease expires. The transmit configuration must be revalidated, and if it is now invalid, the lease subsystem forces the transmitter into a safe configuration (i.e., turns it off). In many systems, this will be an error condition that should never occur in normal operation.

New certificates are presented to the lease subsystem by the baseband subsystem, which receives them over any available communication channel. When a certificate is presented, the lease subsystem must authenticate it before updating the lease table.

Authentication can be performed with a variety of technologies. The obvious one is to cryptographically sign the certificate with a private key known only to the appropriate authority, and then use a public key stored in the lease subsystem to check the signature. This is computationally expensive and may take a long time to perform, perhaps multiple seconds on a lower-end device. This is not a problem in a context where leases last for hours or longer.

In advanced applications, different authorities may control different lease table entries, or multiple authorities may be required to sign a single certificate for it to be accepted. For example, there are business models where different parties contribute separate spectrum access rights to a joint venture; each should control its own lease table entry. Also, a cellular operator may wish to configure the mobile devices in its network to only accept certificates signed by both the manufacturer and the operator. These behaviors are straightforward to support in the lease subsystem. A more complicated question is what the lease subsystem should do when it receives a new lease certificate that overlaps with an existing entry in the table. Multiple approaches are possible, with different behaviors appropriate for different applications.



■ **Figure 3.** *Components of the lease subsystem for an integrated mobile device. Local nonvolatile storage holds the current leases and crypto keys. An optional location sensor can support locationlimited leases.*

Assurance and Trust

For leases to effectively manage the risks of various rights holders, the lease subsystem must be trustworthy. This involves designing it so it can be cost-effectively validated to a high level of assurance. In part, this requires carefully limiting the complexity of the functions it performs.

Moreover, users who physically control the radio devices know that if they can interfere with the behavior of the lease subsystem, they can boost the capability of their devices or possibly get free service. Therefore, attacks by the user are a concern in many applications, as are attacks by the baseband software, since it may not successfully defend itself against the user or third parties. Consequently, the lease subsystem must be secure against both physical and software-based attacks. This is feasible because the lease subsystem is separated from the rest of the radio and exposes only a narrow interface to it. One particular challenge is to make the clock resistant to user tampering, but still allowing time

Frequency range	Power limit	Bandwidth limit	Clock limit
840–850 MHz	1 W	1.25 MHz	8:00AM 08/11/2007
1949–1952 MHz	500 mW	200 kHz	9:00AM 10/24/2008
2400–2500 MHz	500 mW	No limit	No limit

Table 1. *Information in the lease table (notional).*

updates and device battery changes. A secure network time protocol, integral battery backup within the lease subsystem, and GPS are all options.

Lease Systems at the Network Level

Lease extension certificates may be generated and distributed in a number of ways, corresponding to different applications and business models. In the simplest case, there are at least two parties involved: the certificate creator, who is normally the rights holder and the radio user, who installs the certificate in the device. We describe a few interesting variations on the basic approach.

- *Trusted third party*: a centralized lease clearinghouse such as an industry association may collect lease extension information from rights holders and generate the lease certificates for distribution to users, to better enforce trust relationships, or to realize scale/scope economies.
- *Autonomous devices*: the baseband software in a device can be configured to automatically retrieve a new certificate from a known Internet location when the end of the current lease is near, so the user need not be involved.
- *Legal delegation*: for certification leases, the rights holder is the regulatory authority. Rather than generating lease extension messages directly, the regulator may choose to delegate this authority to the manufacturer. Legal sanctions are used to prevent extension of leases when a fielded device causes interference or harm.
- *Spectrum distributors*: a potential player in the future secondary spectrum market is the spectrum distributor [6]. More sophisticated than a spectrum broker, who just matches buyers and sellers, the distributor acquires, aggregates, partitions, and packages spectrum rights and futures. The spectrum distributor can generate the appropriate lease certificates and provide them to the user as part of completing a spectrum transaction.

The lease certificates themselves normally will be fairly short, so they are easy to transmit over any wired or wireless network to the radio device. They contain some representation of the rights being temporarily granted to the radio and an expiration date and time.

We envision two main options for representing transmission rights in a certificate. *Model-independent* certificates specify abstract values such as frequency, power, bandwidth, and so on. *Model-specific* certificates specify particular values for the settings of the devices in the transmit chain.

With model-independent certificates, any entity can generate a certificate, but the lease subsystem must be capable of computing the transmit chain configurations that correspond to the specification. This is straightforward for the simplest leases (e.g., on vs. off) but very challenging for anything more sophisticated. Using model-specific certificates makes the radio itself simpler. However, in most cases only the manufacturer can convert model-independent specifications into a model-specific certificate; this could be a service provided to users and the rights holders they interact with.

Economic and Policy Issues

Costs and Benefits

Lease support in devices and lease management and distribution by networks undoubtedly will add cost to radio systems. However, with the important exception of sensor networks, the cost appears small for most wireless systems. The costs of leases must be analyzed in more detail for specific systems and requirements.

In exchange for their normally small implementation costs, leases offer significant potential benefits, especially for innovative, decentralized, or virally deployed radio systems. If used appropriately, the economic benefits of leases include the following.

- *Lower costs for radio development and certification*: manufacturers have the option of selecting time-limited certification leases to reduce the level of assurance required in certification test.
- *Improved radio efficiency and performance*: use of leases enables manufacturers to cost-effectively certify more aggressive radio designs, or equivalently, to secure consent from spectrum rights holders for more aggressive secondary access etiquettes, both of which promise higher value to users.
- *Reduced risk of incorrect or unapproved operation*: leases enhance ex ante incentives to achieve correctness because the threat of non-renewal offers a credible threat that incorrect operation in the field will result in early termination. The lease mechanism also may be used to enforce upgrades.
- *Lower mitigation costs for incorrect behavior*: leases provide a low-cost, high-assurance mechanism for radio or rights recall.
- *Lower transaction costs for spectrum trading*: assurance that rights can be transferred with predictability and certainty (including that usage will terminate at the expected time) reduces risk and hence reduces the overhead of the mechanisms that would otherwise be used to manage that risk.
- *Lower costs for distributed control*: leases provide a lightweight technical mechanism for collaborating entities to enforce their respective rights and reward others for supportive behavior.

Regulatory Mandates

In our view, lease support should not be mandatory except in special circumstances, such as operation in a band where there is a regulatory sunset clause or other requirement that mandates time-limited radio behavior. In most cases, the decision should be left up to the manufacturer or collaborating parties whether the use of leases offers sufficient benefits to outweigh its costs.

On the other hand, the government may play a useful role in helping the market to coordinate appropriate approaches. The government can guide adoption of lease technology by offering a clear roadmap for certification requirements for advanced radio designs and by considering potential roles for leases when adopting reforms that facilitate the transition to dynamic spectrum access and the emergence of secondary spectrum markets.

Barriers to Adoption of Leases

Despite what appears to be a favorable cost-benefit trade off, and even with regulatory support, leases face a number of challenges to successful commercialization in radio systems.

Potential users fear that even if a radio operates safely and correctly in the field, the lease it requires may not be renewed. One cause for failure is the *ships-at-sea* problem, so-called because the canonical example is a radio on a ship that goes out of communications range for a long period, during which the lease expires but no new certificate can be acquired. Leases may not be appropriate for use in applications such as this, where there are extended periods of disconnection. A lease also might not be renewed due to a *moral hazard* or *hold-up* problem. In this situation, the rights holder uses control over the lease to extract additional value from the user after the initial transaction is complete. Similar moral hazards occur in many situations, such as when a supplier increases the price of its goods after winning an initial order, knowing that the buyer faces high costs in switching to another supplier. There are well-established methods for addressing problems of this type. The most basic is to establish a clear contract at the outset that limits the future behavior of the supplier. For radios, it also may be appropriate to give lease renewal control to a trusted third party such as an industry trade association. Overall, we believe that deploying leases will increase competition through facilitating commercialization of innovative radios and new business models, and so will help reduce the risk of market-power-based opportunistic behavior of all sorts, including the moral hazard problem.

A second concern is that lease-enabled lightweight certification may reduce incentives for manufacturers to design radios that comply fully with regulatory requirements, by making it easier to fix poorly-designed radios *ex post*. In our view, the complexity of advanced radios makes it impossible to design fault-free systems or to fully validate many devices during certification. Given that faults will exist in deployed devices, it is appropriate to develop low-cost strategies for addressing problems when they arise. Moreover, as already noted, the credible threat of non-renewal may actually enhance manufacturers' incentives to achieve full regulatory compliance compared to the current certification approach.

Finally, there is the risk that a certification lease mechanism, if under the control of the regulator, may be used to levy additional taxes on spectrum users, to support more frequent and arbitrary regulatory changes, or otherwise to expropriate additional rents. This is another example of moral hazard, but because of the added concerns about regulatory inefficiency and capture, it is worth identifying this concern separately.

This concern may be mitigated by explicitly limiting the role of the regulator. That is, policymakers should strive toward "technically neutral" regulation that leaves control of lease renewals in the hands of the manufacturer or an industry-sanctioned trusted third party. Clear and simple rules will aid transparency and make credible commitments more feasible, which also will reduce concerns over regulatory commitment and uncertainty.

If the government determines that some sort of fee for spectrum access is appropriate, a lease mechanism introduced to reduce certification barriers would make this tax easy to levy and enforce. This hazard can be addressed through credible commitments that lease renewal will be provided at a pre-specified cost throughout the lifetime of the device.

Conclusion

Time-limited leases are technically feasible to implement at an affordable cost in many radio systems. They offer significant potential benefits for the commercialization and deployment of innovative radios.

The use of time-limited leases is mutually reinforcing with major trends in the wireless market [6]. Leases facilitate dynamic spectrum access, which is synergistic with trends towards decoupling RF spectrum bands from the applications that use them. Leases enable reduction of risk when rights holders collaborate, which is mutually reinforcing with trends towards decoupling of network ownership, spectrum rights ownership, and providing communications services. Leases used in certification limit the harm caused by radios that misbehave. This is increasingly important given the trend toward vertical disintegration in radio manufacturing. Finally, leases enable distributed control over radio behavior, which is an essential enabler in the growing area of end-user owned mesh networking solutions.

As a result of these synergies with important wireless market growth directions, we expect that time-limited leases will play an important role in the emerging ecosystem of innovative radio systems and business models.

Time-limited leases are technically feasible to implement at an affordable cost in many radio systems. They offer significant potential benefits for the commercialization and deployment of innovative radios.

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Biographies

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