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The Technical Basis for Spectrum Rights: Policies to Enhance Market Efficiency

Robert Matheson, radio engineer, retired Dept. of Commerce
Adele C. Morris, Fellow, The Brookings Institution

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Outline

- Motivation
- Explain electrospace basis for spectrum rights
- Ideal version
- Solutions for practical application

Command-and-Control is Increasingly Outmoded

- Specialized bands were optimized for old tech and prevent evolution to newer systems.
- Many new-technology bands are becoming too complex for central planning.
- This problem will only get worse.

What does it take to achieve and sustain efficient spectrum resource allocation?

- Efficient partition of spectrum into licensed, unlicensed, exclusive federal, etc.
- For licensed: efficient primary and secondary markets
  - License auctions, incentive auctions, spectrum markets
- **Focus here: Efficient design of that which is auctioned**
  - **Structure the bundle of rights in a license so markets can work.**

Economically Efficient Exclusive Rights

- Regulator must design rights system.
- Flexibility consistent with the squirrely properties of radio signal propagation:
  - Markets allocate resource
  - Achieve an efficient level of interference
  - Provide efficient incentives to provide service and innovate

Electrospace Dimensions

Electrospace (described by Hinchman in1969) is a 7+ -variable description of electromagnetic field strength (hyperspace).

- Physical location – lat., long., altitude 3-dimensions
- Frequency – MHz 1-dim
- Time - μS, hours, or years 1-dim
- Direction-of-propagation – azimuth, elevation 2-dim

A sufficiently good receiver can separate signals having non-identical electrospace descriptions.

An Electrospace Volume

A subset of the full electrospace that occupies a range in each of the dimensions

- Physical 3-D volume or set thereof
- Frequency band
- Duration
- Set of angles through which the direction-of-propagation may lie

Our proposal: articulate the rights to access spectrum as an electrospace volume and a set of power rules.

i.e. Licensed electrospace region (LER)

Managing Interference with Electrospace-Based Rights

- Licensed electrospace regions include only signal properties of rights holder.
- More signals need more rights.
- As long as LERs are disjoint, interference adjudication is straightforward.

Why Traditional Interference Protection is Economically Inefficient

Interference: any distortion of the desired signal caused by other signals.

- Co-channel operation, excessive sidebands, intermodulation in receiver, receiver overload, etc.

- External costs depend on performance of the receiver.

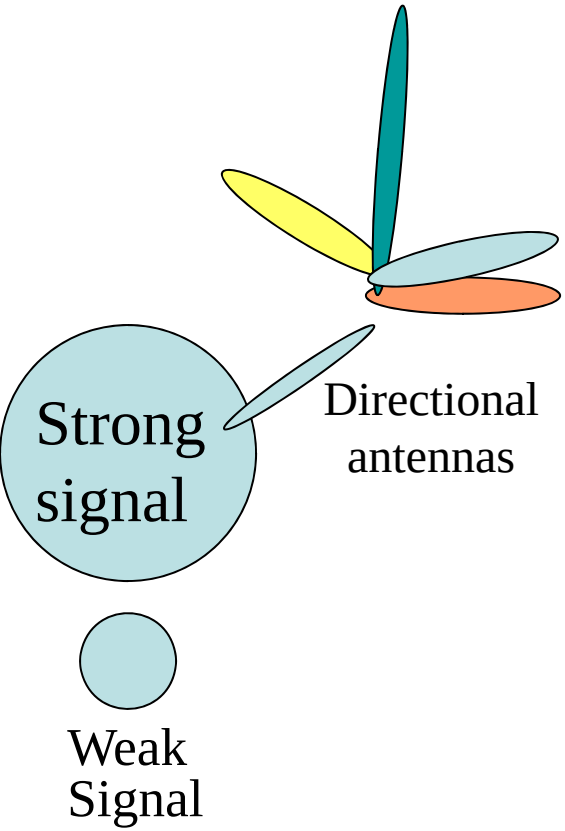
Need market to balance cost and benefit of interference reduction on both demand and supply side.

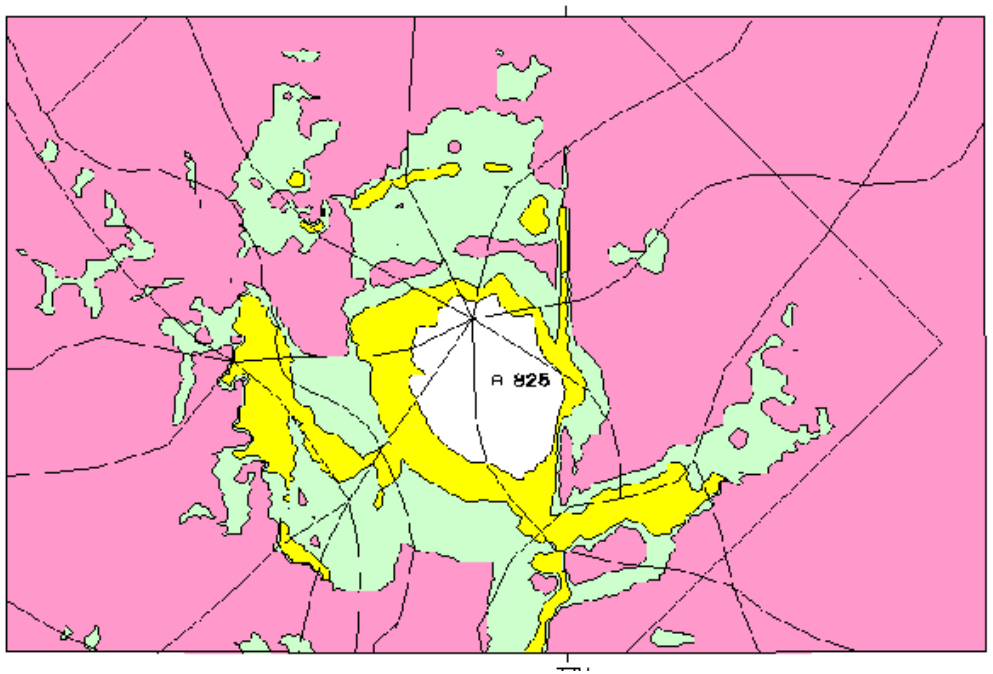
- "Interference protection" can mean "protecting inefficiency."

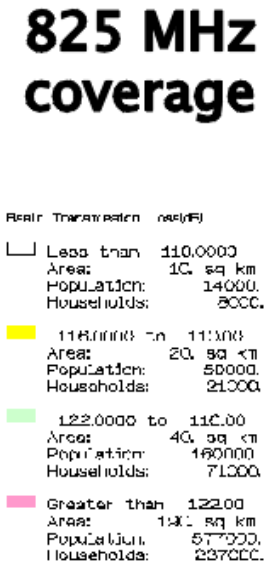
What would happen in other industries if inputs were sold in units of the outputs they produced?

Spatial Dimensions

Any 3-D region: microcell to nationwide. Some geographical areas are complex; coverage affected by terrain and buildings, height above ground.







Frequency Dimension

The frequency dimension is well behaved and intuitive.

Regulators divide some frequency bands into many identical non-overlapping channels.

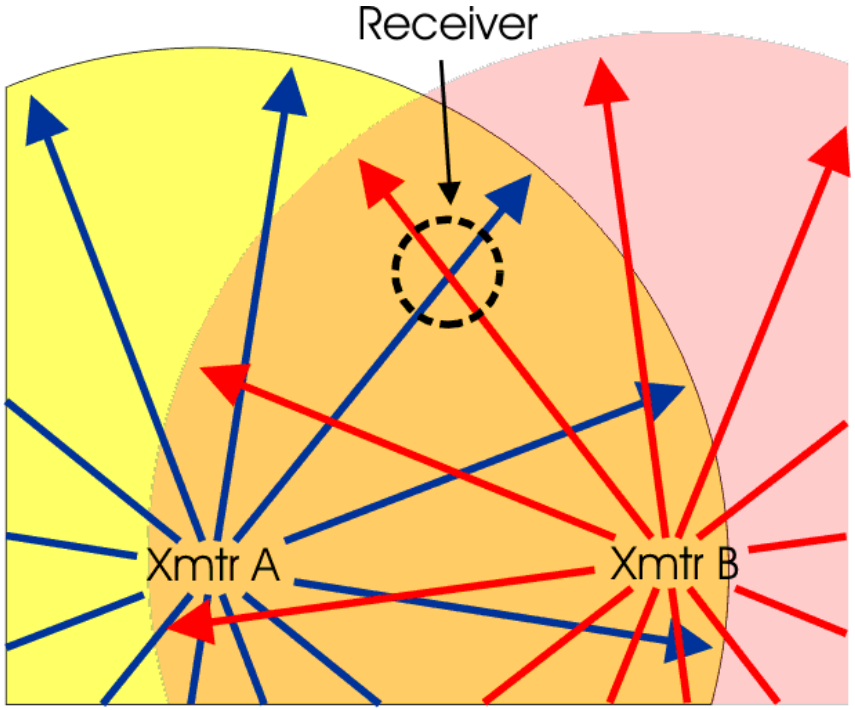
- May be many other ways to divide rights.

Time Dimension

Years	– legal duration of a license
Months	– seasonal uses
Hours	– to broadcast special football game
Hours	– midnight-to-5am daily for backup
10 ms	– TDMA timeslots every 50 ms.

Useful for serving many intermittent activities.

Direction of Propagation



Direction of radio waves near receiving antenna allows detecting individual radio signals.

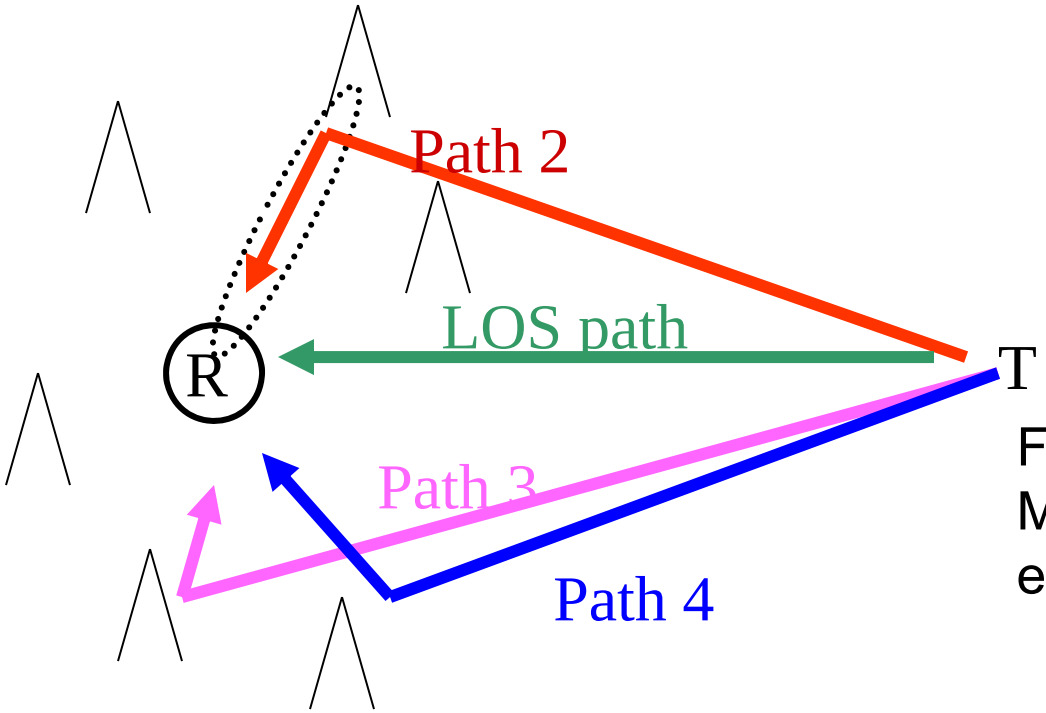
Exploited in fixed point-to-point microwave and geosynchronous satellite systems, radar systems.

Maybe useful for smart phones.

Direction of Propagation

1. Narrowbeam line-of-sight path (pt-pt microwave).

2. Multiple paths between transmitter and receiver reflected from landscape.



Future technologies (e.g. MIMO) will increasingly exploit this dimension

Different services exploit different electrospace dimensions

- Point-to-point microwave has pencil-shaped coverage areas and divides up angle-of-arrival.
- Trunked radio systems adaptively divide time.
- MIMO mathematically finds multiple paths by processing angle-of-arrival part of electrospace.
- Advanced systems will exploit the electrospace in ways we can't predict.

Dimensions not in LER

- Polarization and Modulation
- Require a lot of coordination.
- With current technology, large scale partitioning across these dimensions among unrelated parties is unlikely.
- Not ripe for separate licensing.

Ideal Flexible Rights Rules

Only two rules:

1. Keep your signals within your licensed electrospace volume (no signals permitted outside region).
2. Use ideal receivers to avoid interference from electrospace neighbors.

Any services, technologies, architectures, transmitter powers, modulations, etc. are permitted, as long as these two rules are obeyed. (Replaces all of 47CFR and NTIA Manual)

Perfect, except …

1. Can't reduce signals to *zero* outside licensed electrospace region.

2. Can't build or buy an ideal receiver.

(Otherwise, everything is fine.)

What rules can provide most of the advantages of the ideal?

Practical Flexible Rights Rules

Only two rules:

1. Keep your signals within your licensed electrospace region. (no signals larger than E_0 permitted outside region).
2. Power limitations on transmitters inside licensed electrospace regions to lessen the need for high-performance receivers. (E_{max} rule)

Solutions to Practical Application

1. **"Zero signal outside LER" becomes**
   a. Very small signal outside LER
   b. Definitions of "outside" and "very small" are important

2. **"Use ideal receiver to reject interference"** becomes "Balance benefits of cheaper receivers with costs of signal limits."

3. **Divide and aggregate on secondary market**, but monitor implications for total emissions.

Practical Electrospace Rules

Rule 1: Keep signals within licensed electrospace region. Signals outside < E_0

Define a very small signal, E_0, as being close enough to zero.
E_0 = "minimum" signal or "allowable leakage" signal.

E_0 is power spectral density (PSD) = W/m^2/MHz. Anything above E_0 is a "signal". All signals must remain within the LER.

Choose E_0 such that it won't cause interference to normal system performance.

But: E_0 can have different values in different frequency bands.

E_{max} rules

1. Unlimited power → Maximum power limit → maximum field strength limit (at ground level?) = E_{max}.
   (Receivers are overloaded by high field strength at receiver antenna, not merely transmitter power.)

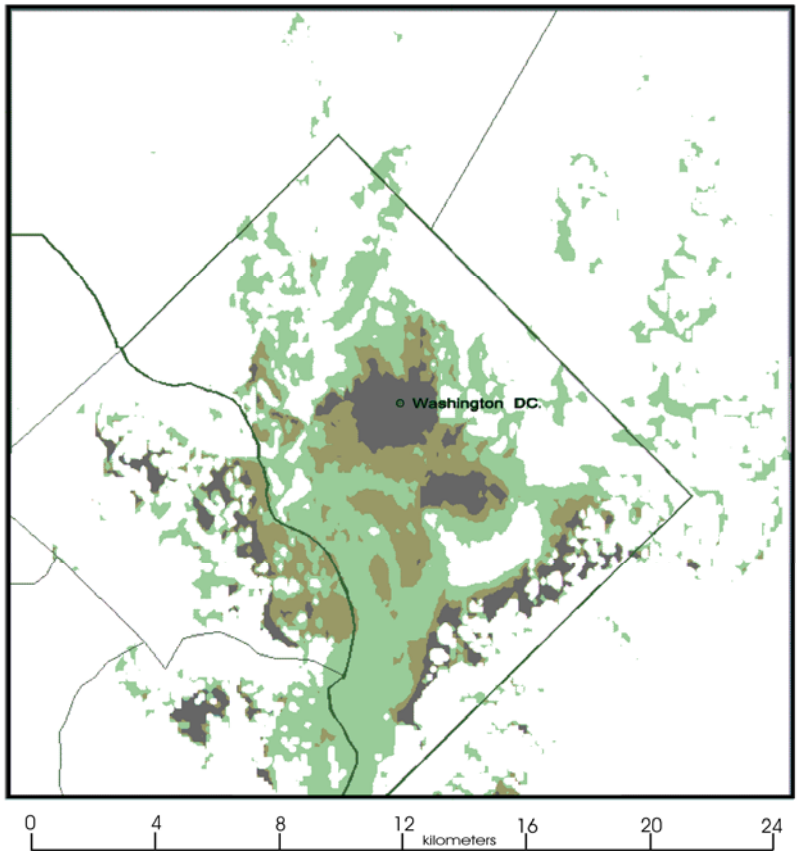
2. Combine transmitter power, antenna location, and antenna vertical patterns to control field strength < E_{max} in locations where foreign receivers might be found.

3. E_{max} is not technology neutral, but it's better than what we have. Point is to explicitly balance benefits from higher transmitter power against costs of out-of-band interference in receivers.

More Practical Issues

- Height
- Probabalistic propagation

E_0: Coverage and Height



Coverage at measurement heights of 2m, 10m, and 50m.

50% probability

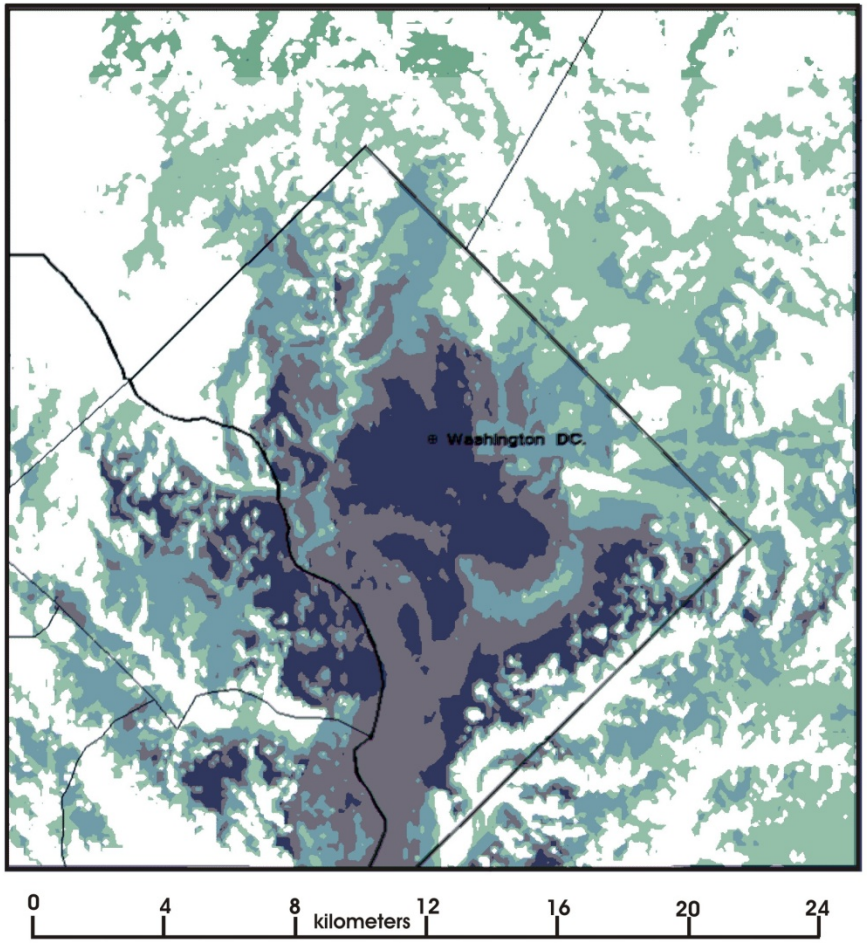
2 m height

10 m height

50 m height

The coverage area increases with measurement height. We can specify the footprint of the electrospace region at a standard height. Ensure the signal is below E_0 only under that standard height.

E_0 and Coverage Variability



Coverage at 10 m height, fixed field strength.

Coverage model shows coverage area increases greatly with lower probabilities. Allow signal to exceed E_0 outside LER only 1% or 0.1% of time.

LER Approach Allows Underlays

- Wireless links, Bluetooth, Wi-Fi, cordless phone, proximity sensors, etc. fall below E_0 so don't count as a signal.

- Encumber so little electrospace that the transaction cost of managing is more than the electrospace is worth.

- Need to be wary of accumulated signal from multiple emitters?

LER Approach Allows Dynamic/Opportunistic Access

- Overlays can assume that any unused spectrum is available.

- Can't be positive you won't cause interference because it's impossible to detect receivers.

- LER offers clear, definitive rights of access
  - All relevent dimensions fully specified
  - Allows dynamic lookup of available/excluded rights

- A lot of licensed spectrum is used only rarely in limited locations. Key: keep transactions costs low to allow easy reallocation.

Flexible Use Questions

- Need details and more research
- Will freedom preclude economy-of-scale services?
- Will indefinite rights complicate future regulatory changes?
- Does extra flexibility make interference more expensive?
- Harder for regulators?

Summary of Electrospace Approach

- Regulators partition spectrum rights across 7 dimensions; each partition is a licensed electrospace region (LER).
- Regulators set up power rules in each band and devolve LERs.
- Licensees may buy, sell, aggregate, and subdivide their LERs at will.
- Power level must be less than a regulated limit (E_0) outside the LER, with exceptions allowed with a specified probability.
- Power or field strength within their LER to a regulator-set maximum (E_{max}).
- Authorities maintain a detailed database and propagation model to support transactions and interference adjudication.