Interference Temperature

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Introduction

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- Using this model, *Cognitive Radios* operating in licensed frequency bands would be able to measure their current interference environment and adjust their transmission characteristics so as not to raise the interference temperature over a regulatory limit.

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- Currently, they do a detailed analysis of the surroundings and rely on worst case analysis.
- But relying on worst case analysis leaves much of the spectrum unused.

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  Technological advances have led to increased diversity of spectrum-based consumer applications. This has resulted in an increased demand for spectral resources. Static interference management does not work anymore.
- **Increased density and mobility**
  People are owning more cellular devices. Density of mobile devices has increased and interference management has become more complicated.

Definition of Interference Temperature

Interference temperature, T_I is defined as

$$T_I(f_c, B) = \frac{P_I(f_c, B)}{kB}$$

where

- $P_I(f_c, B)$ is the average interference power centered at frequency, f_c, and covering bandwidth B.
- k is the Boltzmann's constant $k = 1.38 \times 10^{-23} J/K$

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In SI system, the unit of interference temperature turns out to be *degrees Kelvin*.

Interference Temperature Models

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1. Ideal model
2. Generalized model

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Ideal model

In the ideal model we try to guarantee that

$$T_I(f_i, B_i) + \frac{M_i P}{k B_i} \le T_L(f_i) \qquad \forall \quad 1 \le i \le n \tag{1}$$

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where

- $T_I(f_i, B_i)$ is the interference temperature of the i'th receiver with center frequency f_i and bandwidth B_i
- P is the power of the unlicensed transmitter
- M_i is a constant between 0 and 1 representing the attenuation of the transmitted power P at the i'th receiver, and
- $T_L(f_i)$ is the interference temperature limit of the i'th receiver at center frequency f_i.

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Usually, a unified factor M is used instead of M_i's because we do not know the distance of every receiver. The factor M is fixed by the regulators.

Challenges in implementing the ideal model

- Hard to differentiate between licensed and unlicensed signals unless we already know the coexisting transmitters in the surrounding environment.
- Difficult to measure the interference temperature T_I in the presence of a licensed signal.
  - We can determine the noise floor only if the signal power goes to zero periodically. For that we have to know when the signal power is going to be zero.
  - The other way is to take an average of the noise floor just outside the licensed signal band, but we need to have information about the licensed signal's properties, like center frequency and bandwidth.

Generalized model

The generalized model assumes that we have no a priori knowledge about the signal environment. Thus the constraint in this model has to be written in terms of the unlicensed transmitter's parameters.

$$T_I(f_c, B) + \frac{MP}{kB} \leq T_L(f_c) \tag{2}$$

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where

- $T_L(f_c)$ is the interference temperature limit of the unlicensed transmitter,
- $T_I(f_c, B)$ is the interference temperature of the unlicensed transmitter,
- P is the power of the unlicensed transmitter, and
- M is a constant between 0 and 1 representing the factor by which the transmitted power gets attenuated.

Generalized model (continued)

- If we constrain the transmitted power P to be less than that in the ideal model, from the equations (1) and (2) we have,

$$B(T_L - T_I(f_c, B)) \leq B_i(T_L - T_I(f_i, B_i)) \qquad \forall \quad 1 \leq i \leq n$$

If every receiver receives a power P_i and if the noise floor is the thermal noise temperature T_N, then we can rewrite the above equation as,

$$kBT_L(f_c)(B - B_i) + kBT_N \sum_{j=1}^{N} B_j \leq \sum_{j=1}^{N} B_j P_j \qquad \forall \quad 1 \leq i \leq n$$

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- Though $T_I(f_c, B)$ can be measured easily, inclusion of all signals in its measurement gives rise to a more complex interference environment.

Properties of Interference Temperature

The problem with Interference Temperature model is that it is too simple. It tries to quantify interference assuming it to behave like noise. But interference doesn't actually behave like noise because we have defined interference to include all signals other than the one from the licensed transmitter. So, *Interference Temperature* can't model interference well enough.

Spectral analysis of radio signals

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- A nonparametric spectral estimation method is required for this purpose and *multi-taper spectral estimation* turns out to be the best choice.
- Multitaper spectral estimation has a nice property of allowing both reduced bias and reduced variance at the same time.

Multi-taper spectral estimation

This method uses multiple orthonormal tapers to give different estimates of the spectrum. These estimates are averaged to give the final estimate.

For a time series $\{x_t\}_{t=1}^{N}$, the multi-taper spectral estimation procedure determines two things:

1. K orthonormal slepian tapers denoted by $\{w_t^{(k)}\}_{t=1}^{N}$
2. The respective eigenspectra for each of the K tapers

$$Y_k(f) = \sum_{t=1}^{N} w_t^{(k)} x(t) e^{-j2\pi f t}, \qquad k = 0, 1, ...K - 1$$

Multi-taper spectral estimation(continued)

- Most of the energy of the eigenspectra remain confined inside the *resolution bandwidth*, denoted by $2W$ i.e. between $f - W$ and $f + W$. The *time-bandwidth product*

$$p = 2NW$$

  defines the *degrees of freedom* available for controlling the variance of the spectral estimator.

- A spectral estimate based on the first few eigenspectra with the least sidelobe leakage, is given by

$$\hat{S}(f) = \frac{\sum_{k=0}^{K-1} \lambda_k(f)|Y_k(f)|^2}{\sum_{k=0}^{K-1} \lambda_k(f)}$$

  where λ_k is the eigenvalue for the kth eigenspectrum.

Estimation of interference temperature

To get a reliable spectral estimate of the interference temperature, we do two things:

1. Use the multitaper method to estimate the interference at the receiver and
2. Use a lot of sensors to get a good approximation of the space dependent radio environment at the receiver. In case of mobile phones etc, we might have to stick to just one sensor.

Estimation of interference temperature(continued)

Suppose we have M sensors then using K different slepian tapers for each sensor we may form the M-by-K matrix $\mathbf{A}(f)$, where the $\{w_m\}_{m=1}^{M}$ represent the weights attributed to the sensors.

$$\mathbf{A}(f) = \begin{bmatrix} w_1 Y_1^{(1)}(f) & w_1 Y_2^{(1)}(f) & \dots & w_1 Y_K^{(1)}(f) \\ w_2 Y_1^{(2)}(f) & w_2 Y_2^{(2)}(f) & \dots & w_2 Y_K^{(2)}(f) \\ \vdots & \vdots & & \vdots \\ w_M Y_1^{(M)}(f) & w_M Y_2^{(M)}(f) & \dots & w_M Y_K^{(M)}(f) \end{bmatrix}$$

Estimation of interference temperature(continued)

Each element in $\mathbf{A}(f)$ has contributions from both the additive internal noise and the incoming signal. We may get rid of the noise by using *singular value decomposition* to decompose $\mathbf{A}(f)$.

$$\mathbf{A}(f) = \sum_{k=0}^{K-1} \sigma_k(f)\mathbf{u}_k(f)\mathbf{v}_k^\dagger(f) \tag{3}$$

We take the left singular vectors $\mathbf{u}_k(f)$ and the right singular vectors $\mathbf{v}_k(f)$ corresponding to the first few largest eigenvalues $|\sigma_k(f)|^2$. The first few largest eigenvalues $|\sigma_k(f)|^2$ provide a pretty good estimate of the interference temperature.

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