Software defined radio based on the upper audio band for low data rate communication over short distances

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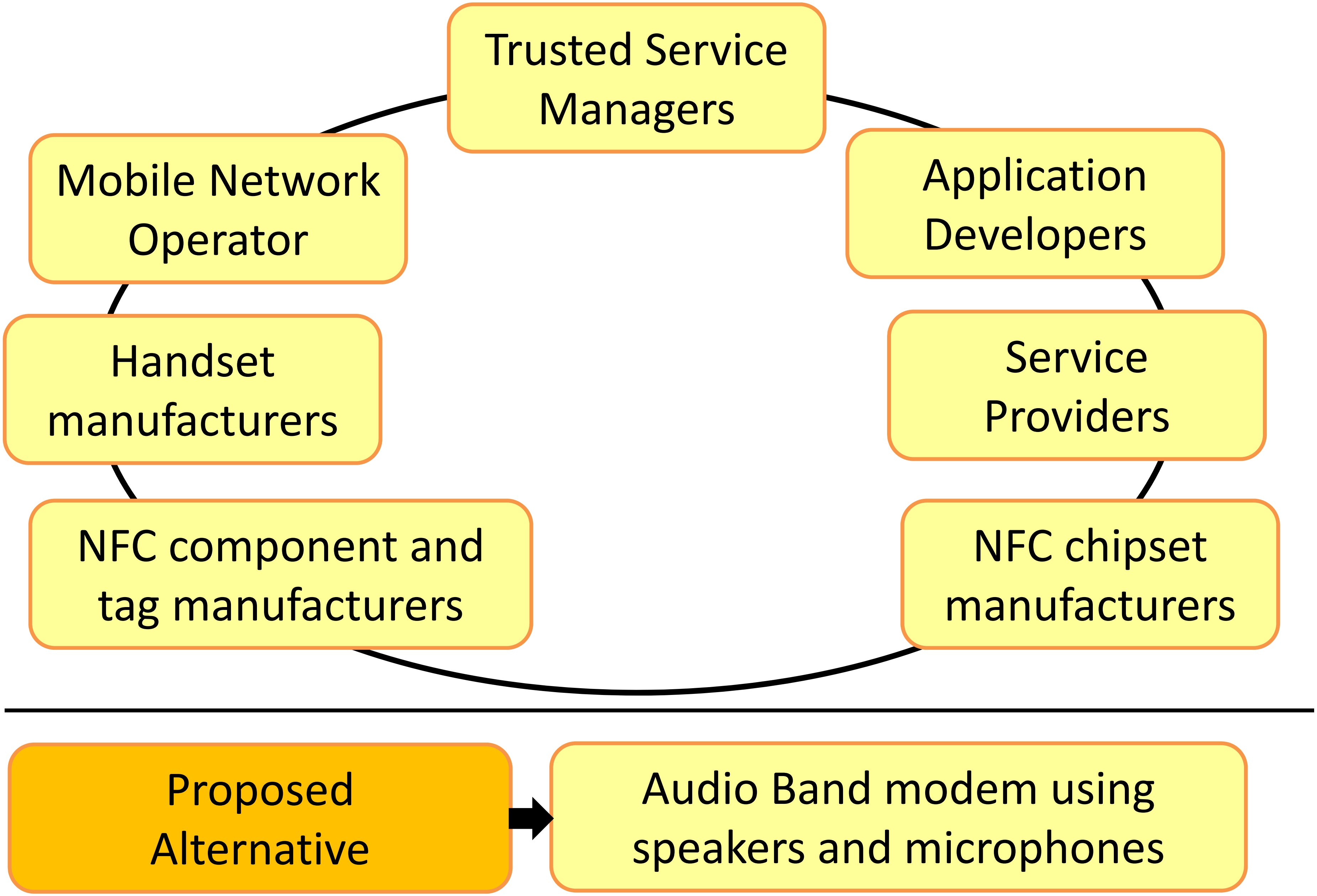
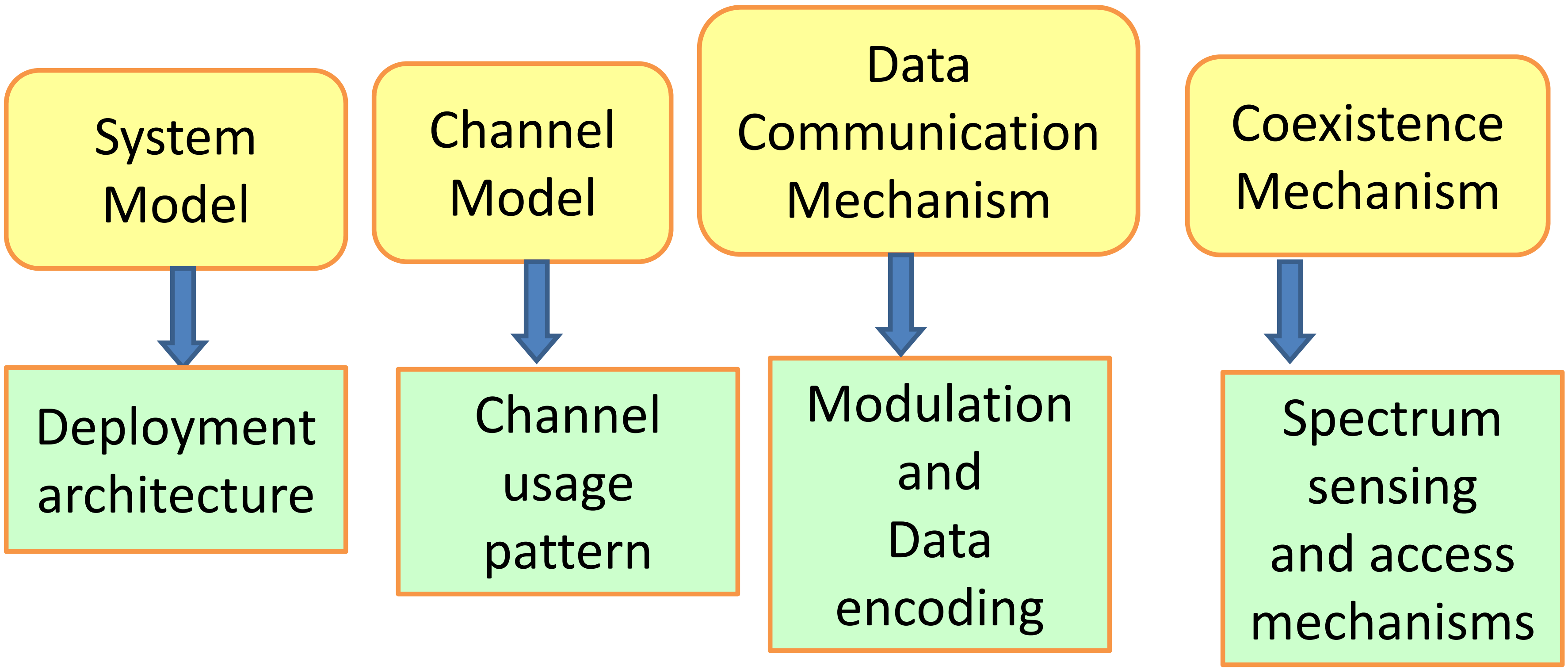
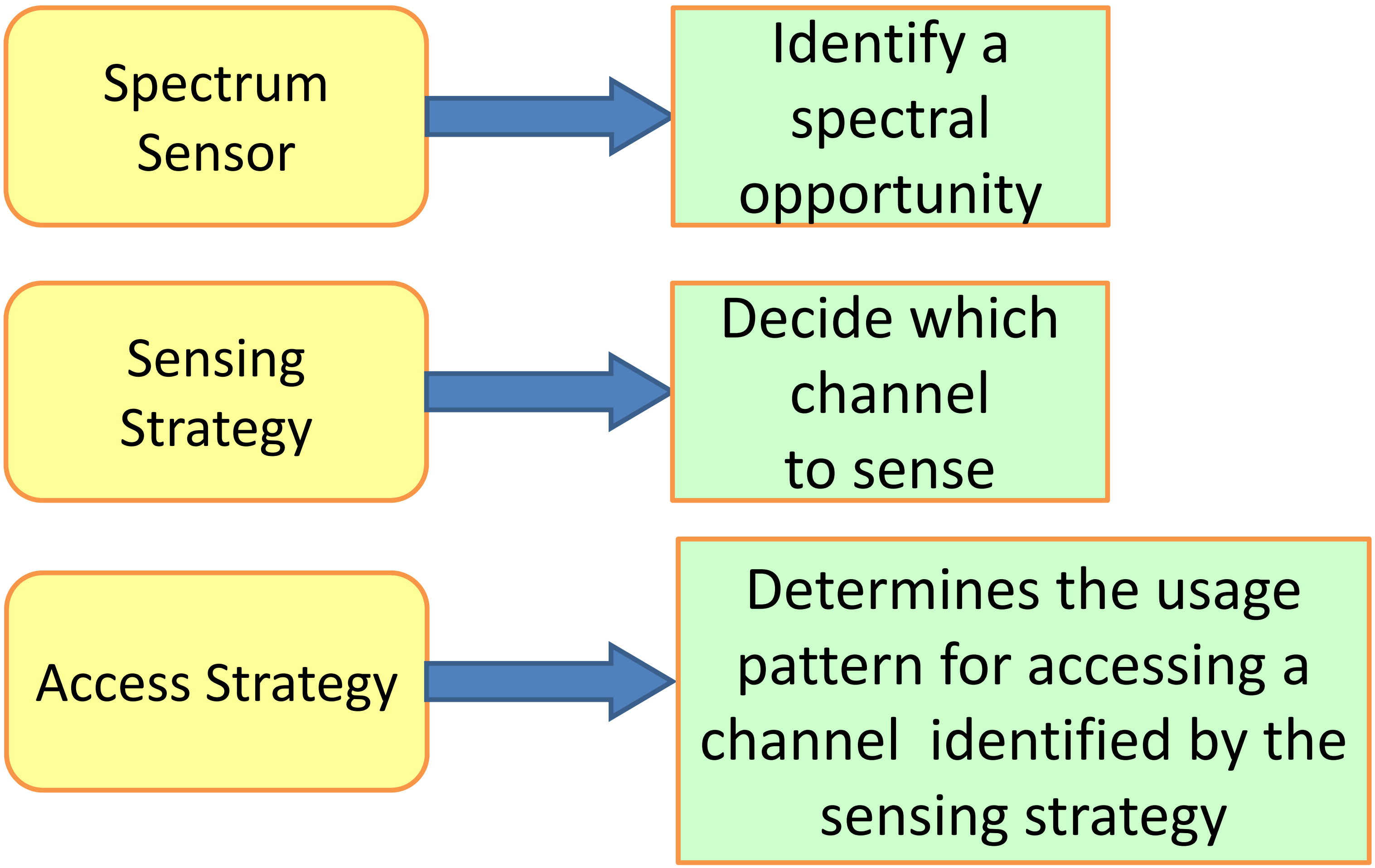
Stakeholders in an NFC Ecosystem



Reconfigurable Audio Band modem Design Guidelines

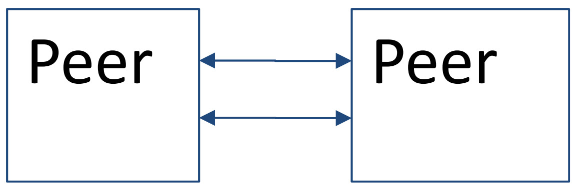


Sensing and Access Mechanism

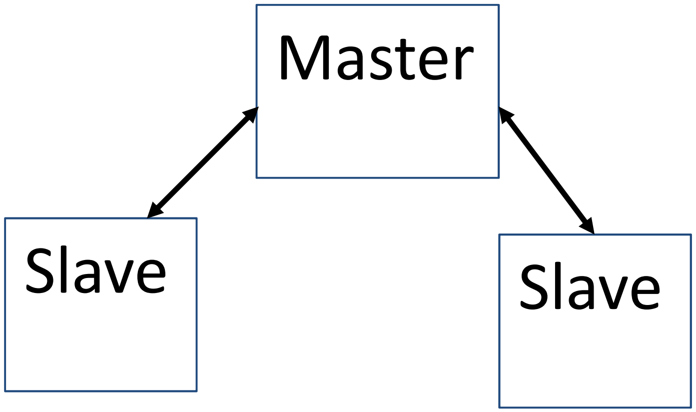


System Deployment Model

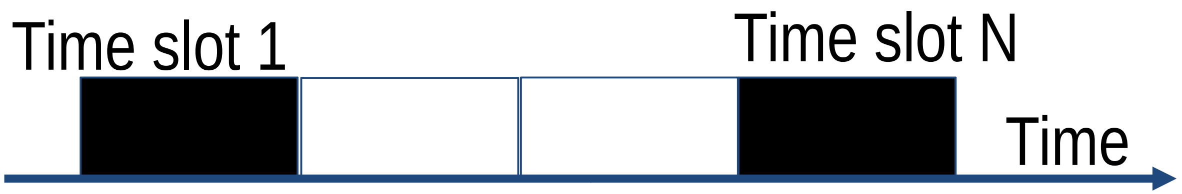
Peer-to-peer



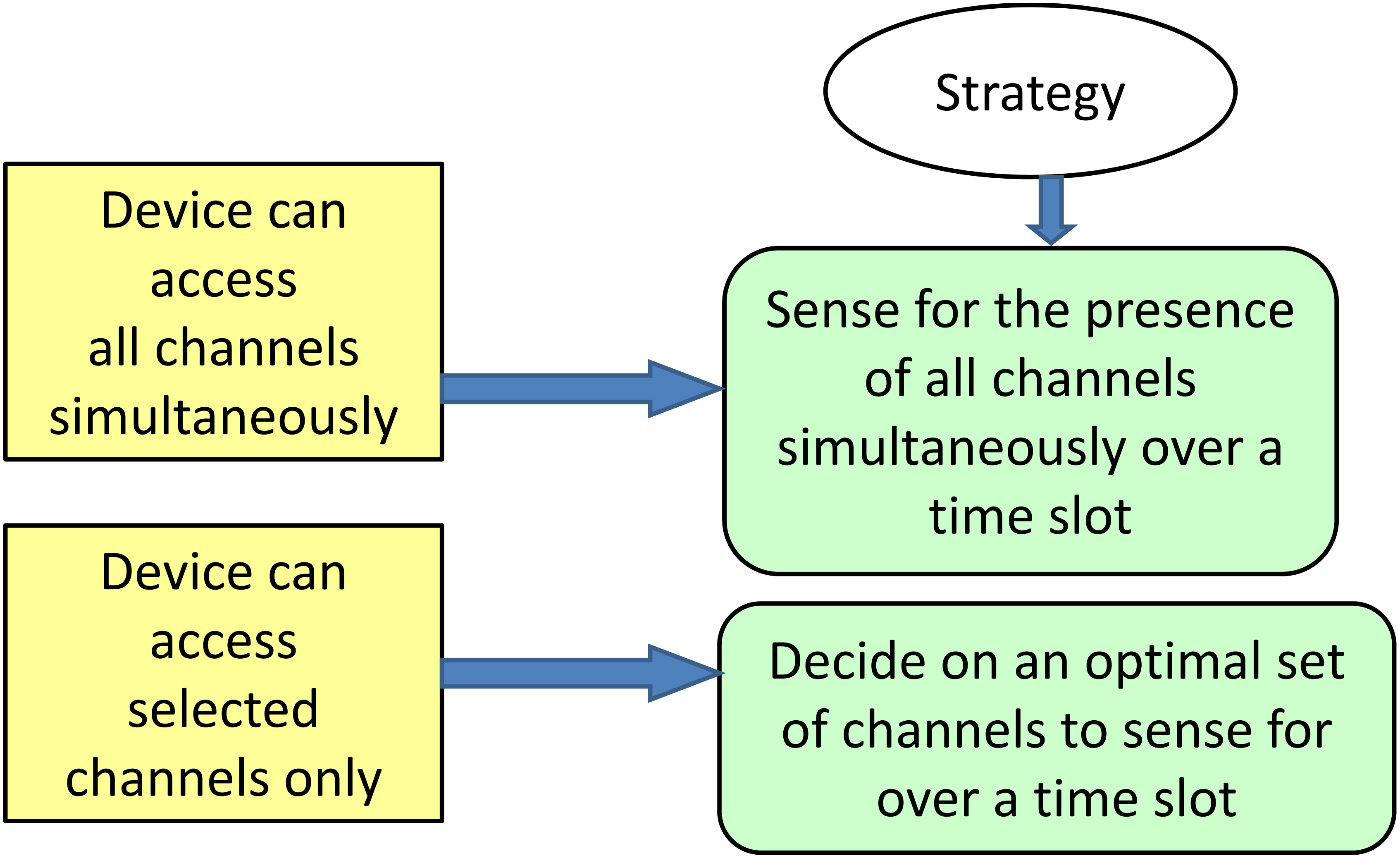
Master slave



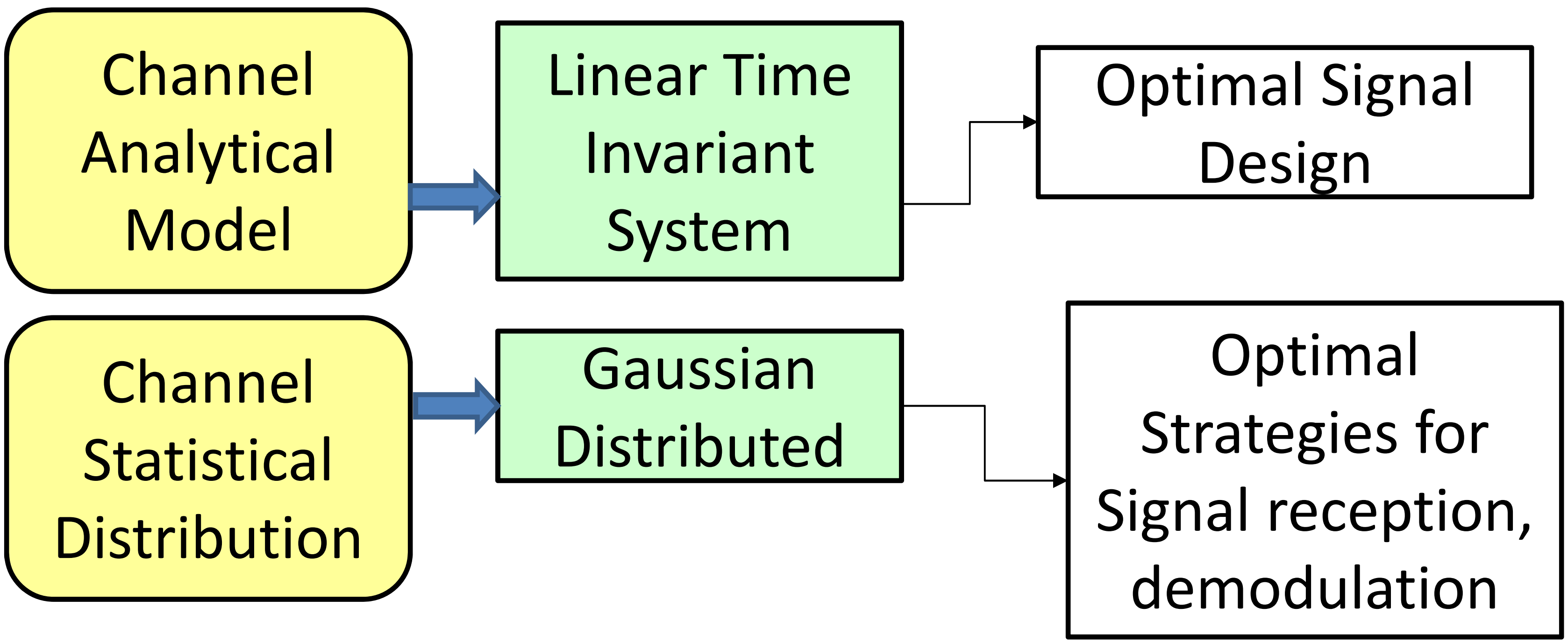
Channel Usage Model (Time Slotted Traffic)



Sensing Strategy



Data Communication Mechanism



Signal Model

Pulse shaped Multi-tone FSK

$$x(t) = p(t).\left[A\cos(2\pi f_1 t) + A\cos(2\pi f_2 t)\right] \quad 0 < t \le T$$

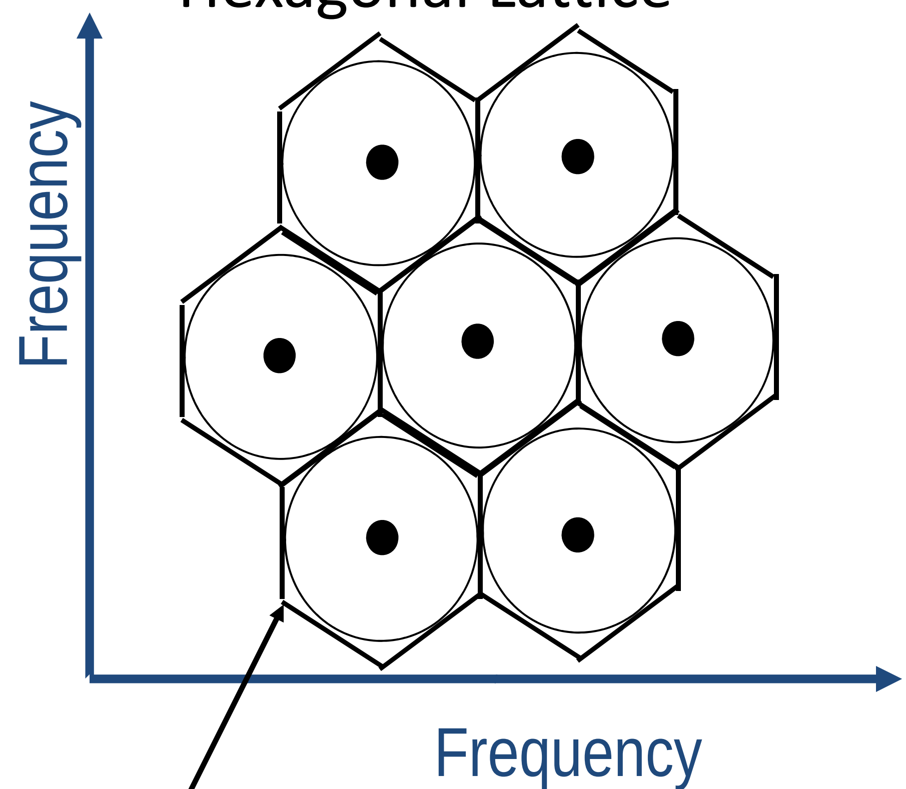
Choice of Frequency Pairs

$$(f_1, f_2)$$

Hexagonal Lattice Structure

Optimal use of Spectrum for a given error rate performance

Hexagonal Lattice



Hexagonal Voronoi Region

Lattice Structures

2D-Hexagonal Lattice For 2-tone FSK

$$M_1 = 13000\,Hz,\ M_0 = 12000\ Hz$$
$$B = [0, 6500]Hz$$

$$G = \begin{bmatrix} 1 & 0 \\ 0.5 & \sqrt{3}/2 \end{bmatrix}$$

$$F_1 = [M_0\ M_0].G + B = [18000, 16892]Hz$$
$$F_2 = [M_0\ M_1].G + B = [18500, 17758]Hz$$
$$F_3 = [M_1\ M_0].G + B = [19000, 16892]Hz$$
$$F_4 = [M_1\ M_1].G + B = [19500, 17758]Hz$$

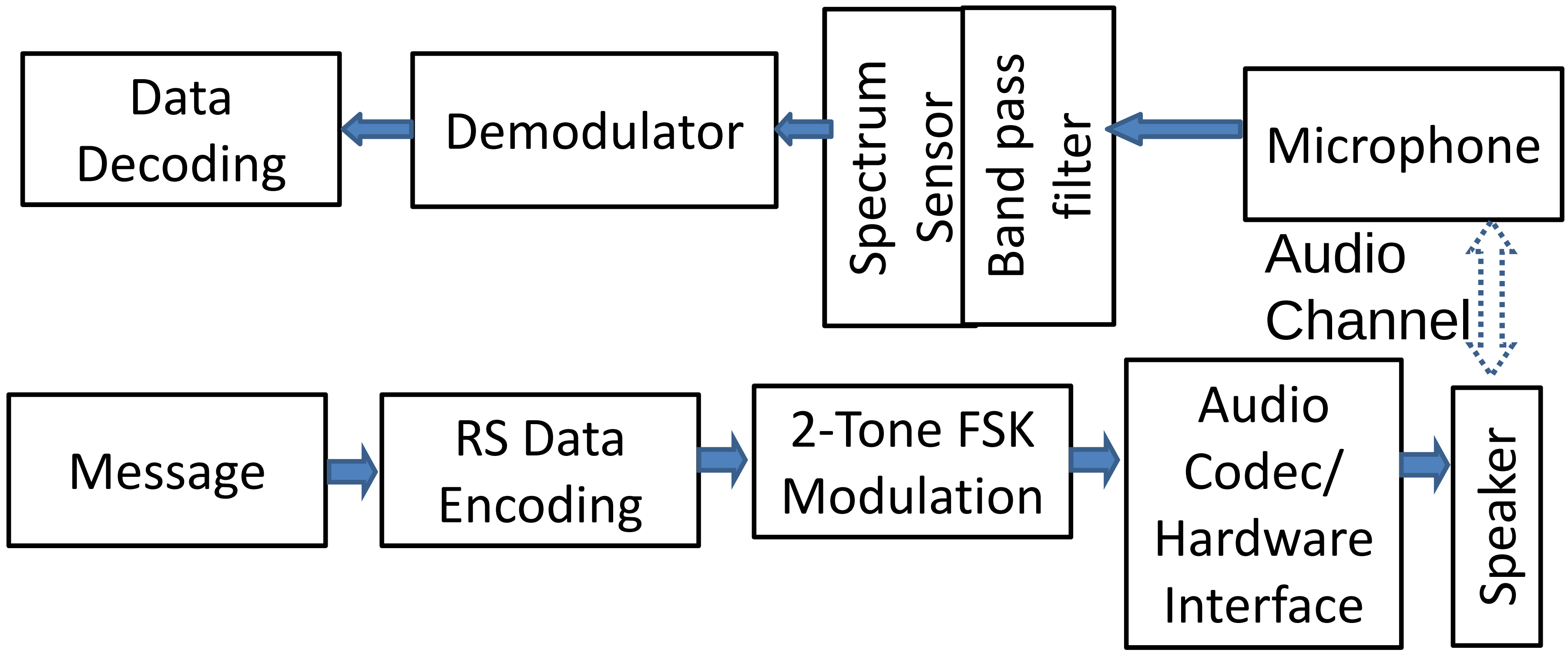
3D-Laminated Hexagonal Lattice for 3-tone FSK

$$G = \begin{bmatrix} 1 & 0 & 0 \\ 0.5 & \sqrt{3}/2 & 0 \\ 0.5 & 0.5/\sqrt{3} & \sqrt{2/3} \end{bmatrix}$$

$$F = [M_i, M_j, M_k]G + B\ Hz$$
$$i, j, k \in \{0,1\}$$

8 Lattice Co-ordinates

Modem Architecture



$[D,[s_1,s_2,s_3,s_4]]$

Message sequence

Flag sequence

(15,9) Reed Solomon (RS) Code over $GF(2^4)$

Encoded Data

$$D=[d_1,d_2,\ldots d_{32}] \quad d_i,s_i \in \{0,1\}$$

Receiver

Noisy Received Sampled Signal

Pulse Shaping

Additive White Gaussian Noise

$$y(n) = p(nt_s).A.\left[\cos(2\pi f_1 n t_s) + \cos(2\pi f_2 n t_s)\right] + w(nt_s)$$

$$t_S = 1/f_S \qquad f_s = 44100\ samples/\sec$$

Peak-picking of Periodogram

$$S(k) = \frac{1}{N}\left|\sum_{n=0}^{N-1} y(n)\exp\left(\frac{-j\,2\pi\,n\,k}{N}\right)\right|^2 k = 0,1,,,N-1$$

Maximum Likelihood Frequency Estimates

$$\hat{\mathbf{f}} = [\hat{f}_1, \hat{f}_2]$$

Receiver

Condition

$$\left|f_{i1}-f_{i2}\right|/f_s \gg \frac{1}{N} \quad i=1,2,3,4$$

Frequency estimates are uncorrelated

Joint Probability Density function of frequency estimates has a diagonal Covariance matrix

Demodulation

$$[f_1^{dec}, f_2^{dec}] = \min_{\{f_{k1}, f_{k2}\}} \left[\left|\hat{f}_1 - f_{k1}\right|^2 + \left|\hat{f}_2 - f_{k2}\right|^2 \right]$$

$$k = 1, 2, 3, 4$$

Probability of Symbol Error

$$P_s = 1 - \frac{1}{4}\sum_{k=1}^{4} \frac{1}{\left(\sigma\sqrt{2\pi}\right)^2} \int_{V(C_k)} e^{-\left[\left|\hat{f}_1 - f_{k1}\right|^2 + \left|\hat{f}_2 - f_{k2}\right|^2\right]/2\sigma^2} d\mathbf{f}$$

Hexagonal Voronoi Region

Spectrum Sensing-Method-I

$$F_1 = [f_{11}, f_{12}] \quad F_2 = [f_{21}, f_{22}] \quad F_3 = [f_{31}, f_{32}] \quad F_4 = [f_{41}, f_{42}]$$

Compute the Un-windowed Periodogram

$$S(k) = \frac{1}{N}\left|\sum_{n=0}^{N-1} y(n)\exp\left(\frac{-j\,2\pi\,n\,k}{N}\right)\right|^2 \qquad k = 0,1,,,N-1$$

Compute a Test Statistic to Detect Presence of Valid Tones

$$r_{k1} = \frac{2N.S(k_1)}{\sum_{k=0}^{N-1} S(k)} \qquad r_{k2} = \frac{2N.S(k_2)}{\sum_{k=0}^{N-1} S(k)} \qquad k_1 = \frac{N.f_{i1}}{f_s} \qquad k_2 = \frac{N.f_{i2}}{f_s}$$

$$i = 1,2,3,4$$

Spectrum Sensing-Method-II

Compute the Short-time Fourier Transform (STFT)

$$S_{\tau}[k] = \frac{1}{N}\sum_{n=0}^{N-1} y[n+\tau N]e^{-j\frac{2\pi nk}{N}}$$

$$k = 0,1,..,N-1$$

Index of Window → $\tau \in \{0,1,\ldots,N_s-1\}$

Number of Windows → N_s

$\mathbf{S}_k\ (N \times N_S)$

$\mathbf{C}_K\ (N \times N)$

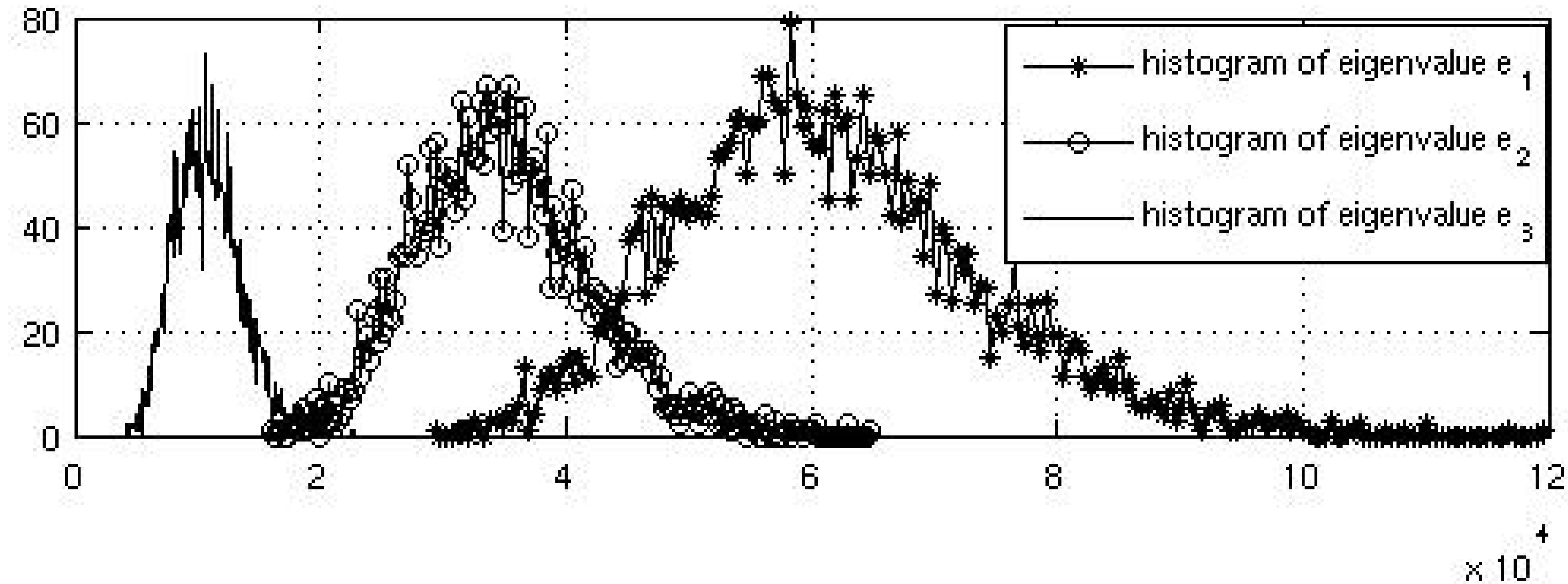
Covariance Matrix estimate of the Short-Time Fourier Transform →

$$\mathbf{C}_K = \frac{1}{K-1}\sum_{k=1}^{K}\left(\mathbf{S}_k - E[\mathbf{S}_k]\right)\left(\mathbf{S}_k - E[\mathbf{S}_k]\right)^T$$

2 Largest Eigenvalues of Covariance Matrix → e_1, e_2 ← Test Statistic

Spectrum Sensing Method II-Using Eigenvalues of Covariance matrix of the STFT

Frequency Of Occurrence



A Threshold on the 2 Largest Eigenvalues allows detection of valid tones for a 2-tone FSK signal

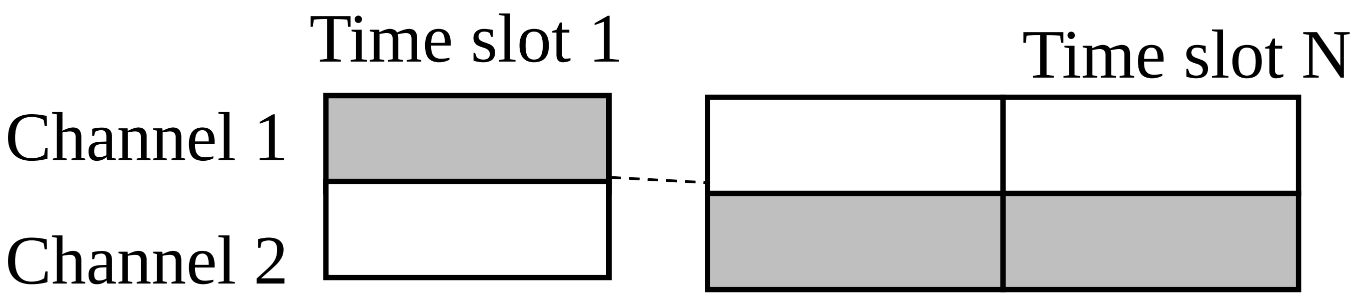
Advantages

- Smaller sensing duration
- Lower probability of false alarm/misdetection

Sensing and Access Strategy

Sensing Strategy → Sense for two Channels simultaneously

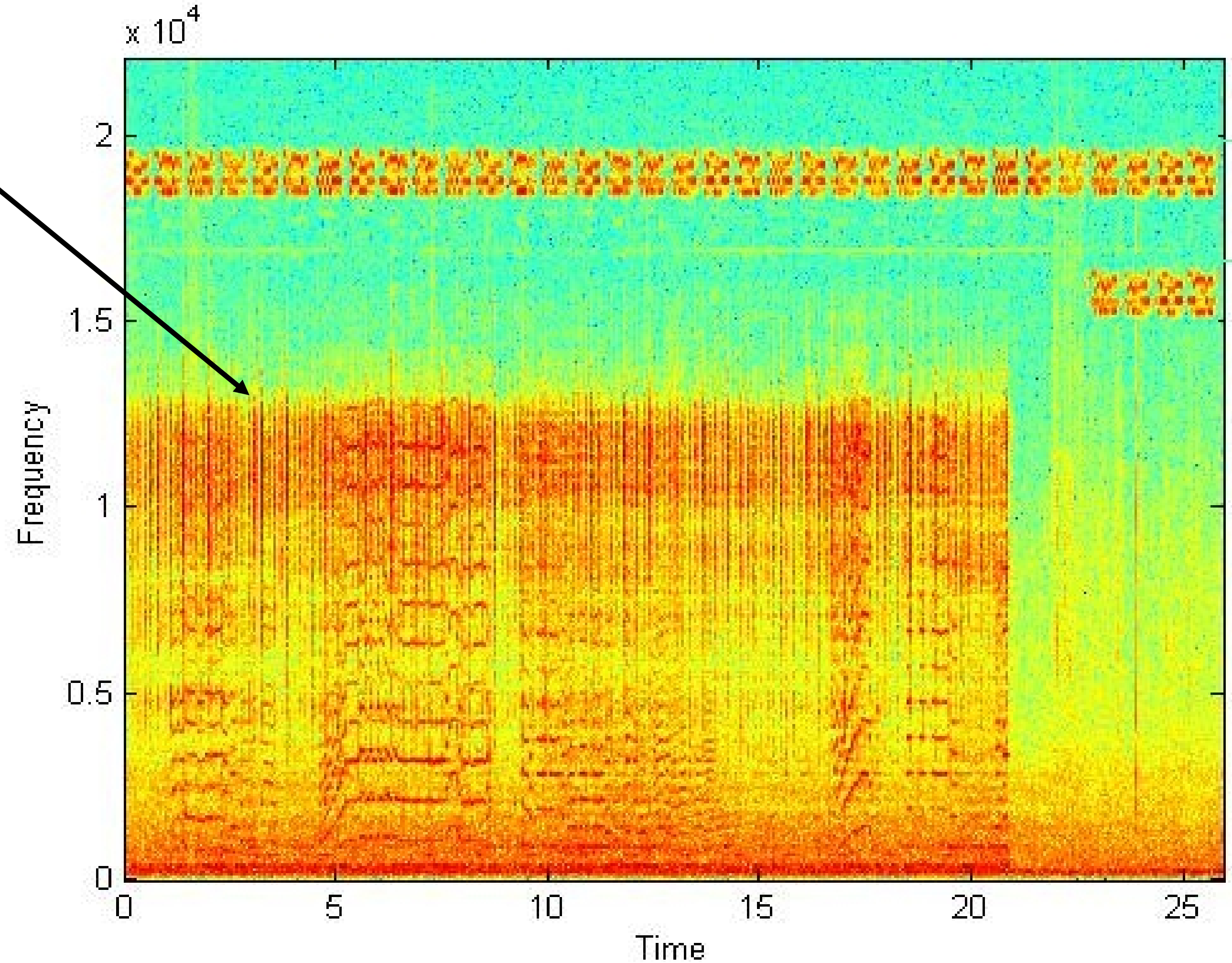
Channel Usage - Slotted Traffic over two channels



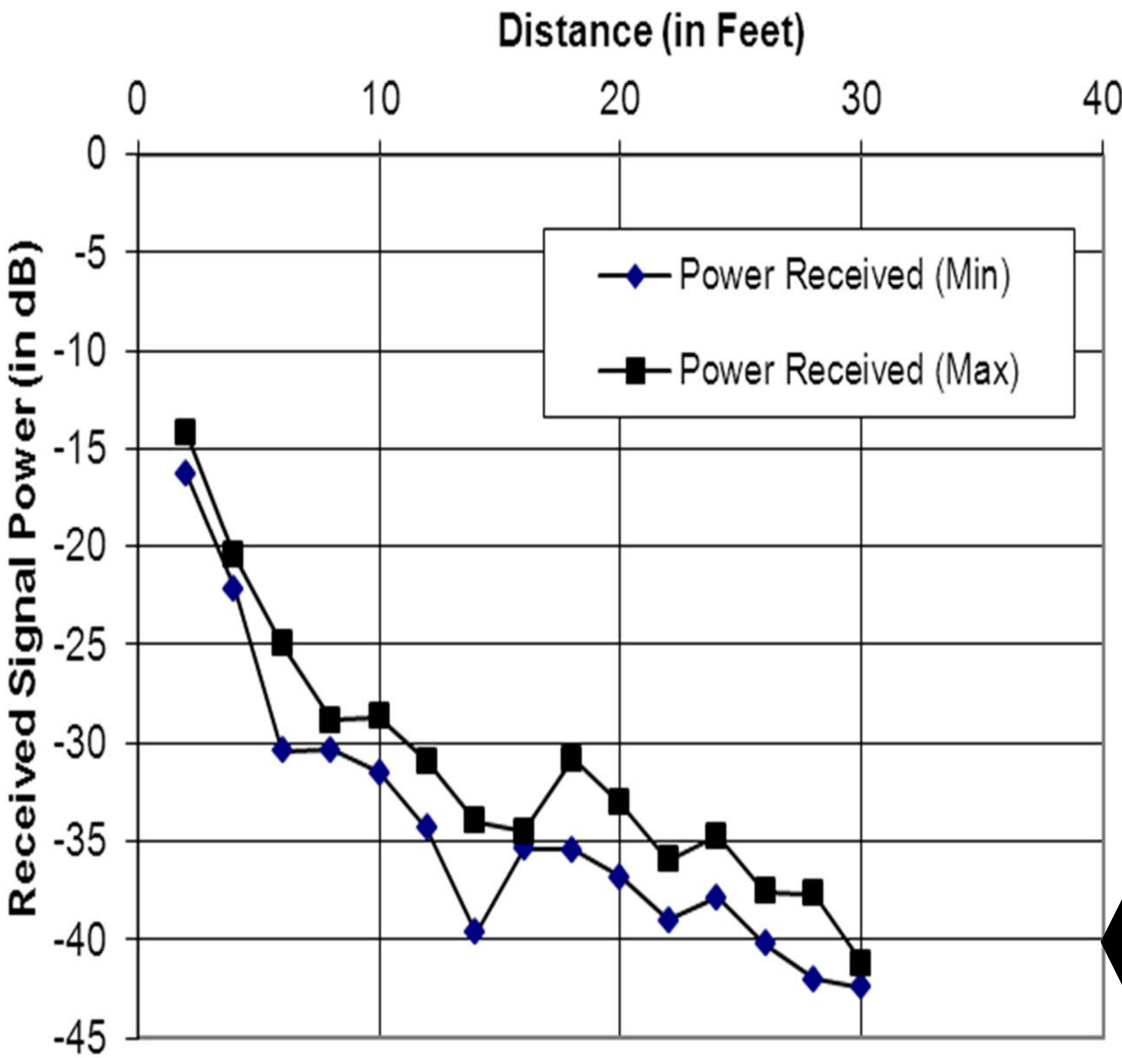
Access Strategy → Access one channel at a time

Spectrogram of Transmitted Signals (2-Tone FSK)

Spectrogram
Of
background
Instrumental
Music



Modem Performance (Coverage)



Data decoding was successful for upto a distance of 20 ft

Speaker spec: 90dB/W/m

Mic spec: 50mV/Pascal

Receiving iPad

Measurements Averaged over Several trials

Modem Performance (Throughput)

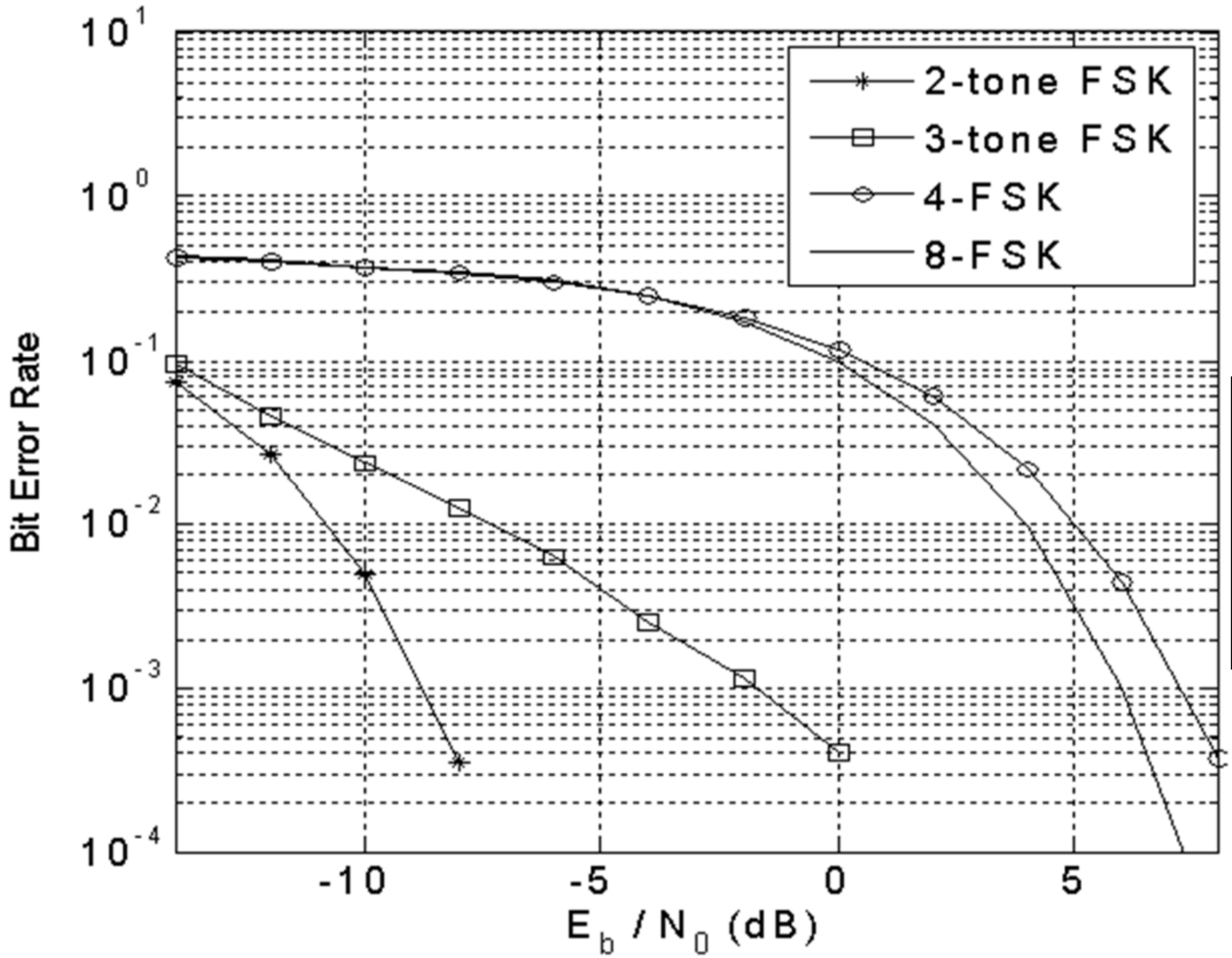
$$\text{THROUGHPUT} = \frac{\text{Identified empty Time-Frequency Slots}}{\text{Total number of Time-Frequency Slots}}$$

	Sensing Duration		
	20ms	13ms	10ms
Distance			
1 feet	0.5297	0.5569	0.5674
2 feet	0.5345	0.5578	0.5679
3 feet	0.5293	0.5544	0.5639
4 feet	0.5360	0.5587	0.5684
5 feet	0.5398	0.5618	0.5709
6 feet	0.5371	0.5601	0.5699

EFFECTIVE THROUGHPUT IMPROVES FOR SMALLER SENSING DURATIONS

Test Statistic- Periodogram (slide 13)

Modem Performance (Error Rate Performance)



Monte-Carlo Simulation of Error rate performance

Un-coded data over Additive white Gaussian noise

Bit Error Rate well suited for communicating data

Summary of Features

Reconfigurable data modem
based on the upper audio band

Peer-to-peer or Broadcast mode of operation

Range 10-20 feet

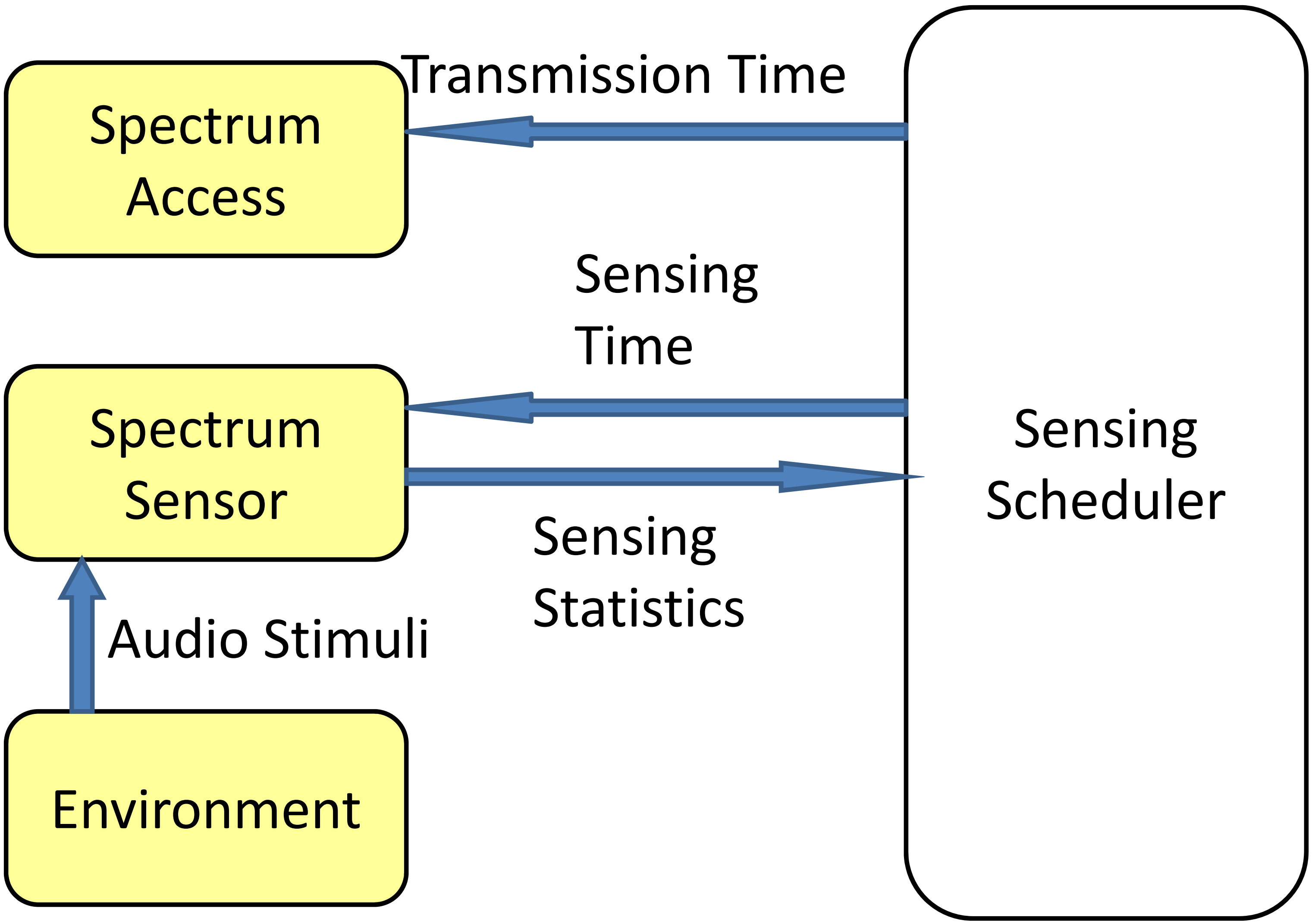
Data rate-300 bps

Portable speakers
and receiving iPad

Spectrally efficient modulation-Multi-tone FSK

Error Control using Reed-Solomon Codes

Work in Progress



Major References

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[2] J. H. Conway and N. Sloane, *Sphere Packings, Lattices and Groups*. New York: Springer 98.

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[4] J. Kim and J. Andrews, "Sensitive White Space Detection with Spectral Covariance Sensing," *IEEE Transactions on Wireless Communications*, vol. 9, Sep 2010.

[5] A. Ghasemi and E. S. Sousa, "Spectrum Sensing in Cognitive Radio Networks: Requirements, Challenges and Design Trade-offs," *IEEE Communications Magazine*, Apr 2008.