An All-GNU Radio Software-defined Radio Transceiver for All-Spectrum Cognitive Channelization

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Outline

- Motivation
- Basic Idea
- Testbed Architecture & Design
- Experimental Results
- Conclusions

Motivation

- Highly occupied spectrum bands + Exponential growth in traffic.
- Underutilization of the device's available/accessible bandwidth.
- Practical co-existence of cognitive secondary and primary stations.
- Hardware radios are application specific. Innovation comes from PHY.
- Need for reconfigurable, agile, intelligently-flexible autonomous radios.

Key question

Are we efficiently utilizing the available spectrum resources?

Cognitive Radio Principles

- Primary/Secondary user setup.
- SU transmissions over gray or white spaces (underlay, overlay, interweave).
- Satisfy QoS constraints at the PT.

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In this presentation ...

- △ Implementation of cognitive channelization on a GNU Radio/USRP framework.
  - SU and PU coexist in both frequency and time. (grey spaces transmissions).
  - SU utilizes a code channel that exhibits minimum interference with PU.
- △ Technical implementation challenges of real-time reconfigurability for channelization (code-domain).

System Setup

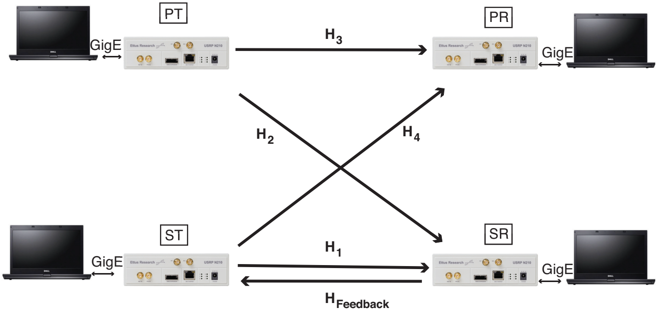

Figure : Primary transmitter-receiver PT/PR and secondary transmitter/receiver ST/SR pairs. All signals propagate over independent multipath Rayleigh fading channels.

Problem Formulation - Signal Model

- PU/SU transmitted signal:

$$x_k(t) = \sum_{i=0}^{J-1} b_k(i)\sqrt{E_k}d_k(t - iT)e^{j(2\pi f_c t + \phi_k)}, \quad k = 1, 2 \text{ for PU/SU.}$$

- $b_k(i) \in \{\pm 1\}$, binary antipodal information symbols.
- $k = 1, 2$ for primary/secondary user respectively.
- E_k: transmitted energy per bit.
- $d_k(t) = \sum_{l=0}^{L-1} s_k(l) g_T(t - lT_d), \quad \text{where} \quad \mathrm{s_k(l)} \in \frac{1}{\sqrt{\mathrm{L}}}\{\pm 1\}.$
- $g_T(\cdot)$: SRRC pulse-shaping filter.
- ϕ_k: carrier phase relative to the carrier frequency f_c.

Problem Formulation - Signal Model (cnt'd)

- Received baseband signal after carrier demodulation:

$$r(t) = \sum_{i=0}^{J-1} \sum_{k=1}^{2} b_k(i) \times \sum_{n=0}^{N-1} h'_{k,n} d_k(t - iT - nT_d - \tau_k) e^{-j(2\pi \Delta f_k t)} + n(t), \quad k = 1, 2$$

- where $h'_{k,n} = \sqrt{E_k} h_{k,n} e^{-j(2\pi f_c n T_d) + \gamma_k}$, and $\gamma_k = 2\pi f_c \tau_k - \phi_k$.
- $h_{k,n}$: independent zero-mean complex Gaussian channel coefficients.
- $\{\Delta f_k\}$: carrier frequency offsets between any TX-RX pair.
- $\tau_k = \kappa_k T_d$: propagation delays w.r.t ST for $\kappa_k \in \{0, 1, \dots L - 1\}$.
- $n(t)$: CWGN.

Reconfigurable Channelization: Optimal Waveform Design

- Denote secondary user's signal of interest as $b_1\mathbf{H}_1\mathbf{s}_1$.
- Denote cumulative interference as $\mathbf{p}_i + \mathbf{n}_i$.
- If $\mathbf{H}_1$ is known then,

$$\mathbf{w}_{\mathrm{maxSINR}} = \arg\max_{\mathbf{w}} \frac{\mathrm{E}\{|\mathbf{w}^{\mathrm{H}}(\mathrm{b}_1\mathbf{H}_1\mathbf{s}_1)|^2\}}{\mathrm{E}\{|\mathbf{w}^{\mathrm{H}}(\mathbf{p}+\mathbf{n})|^2\}}$$

$$= (\mathbf{R}_p + \sigma_n^2\mathbf{I}_{N+L-1})^{-1}\mathbf{H}_1\mathbf{s}_1$$

is the linear filter maximizing the SINR at the output of the SR.

- Let $\mathbf{R}_{\mathrm{I+N}} = \mathbf{R}_p + \sigma_n^2\mathbf{I}_{N+L-1}$, then the maximum SINR attained is

$$\mathrm{SINR}_{\max} = \mathbf{s_1}^{\mathrm{T}}\mathbf{H}_1^{\mathrm{H}}\mathbf{R}_{\mathrm{I+N}}^{-1}\mathbf{H}_1\mathbf{s}_1.$$

Reconfigurable Channelization: Optimal Waveform Design (cnt'd)

- Now consider $\mathrm{SINR}_{\max}$ as a function of waveform $\mathbf{s}_1$.
- Then,

$$\mathbf{s}_1^{\mathrm{opt}} = \arg\max_{\mathbf{s}_1} \left\{ \mathbf{s_1}^{\mathrm{T}} \mathbf{H}_1^{\mathrm{H}} \mathbf{R}_{\mathrm{I+N}}^{-1} \mathbf{H}_1 \mathbf{s}_1 \right\}$$

  maximizes the SINR at the output of the maximum SINR filter.
- Define

$$\widetilde{\mathbf{M}} \triangleq \mathbf{H}_1^H \mathbf{R}_{\mathrm{I+N}}^{-1} \mathbf{H}_1,$$

  where $\mathbf{q}_1, \mathbf{q}_2, \ldots, \mathbf{q}_L$ denote its eigenvectors with corresponding eigenvalues $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_L$.
- Then, $\mathbf{s}_1^{\mathrm{opt}}$ is the eigenvector that corresponds to the maximum eigenvalue λ_1.

Implementation Challenges

- Unknown chip timing
- CFO's $\{\Delta f_k\}$

$\Big\}$ I&D operation will lead to SNR loss.

- No cooperation assumed between PU-SU.
- Maximal-SINR waveform design for SU ($\mathbf{H}_1$ and $\mathbf{R}_{\mathrm{I+N}}$ are unknown).
- Spread-spectrum receiver design.
  - Frame Detection.
  - CFO estimation/compensation.
  - Symbol time synchronization.
  - Maximum SINR RAKE filtering.

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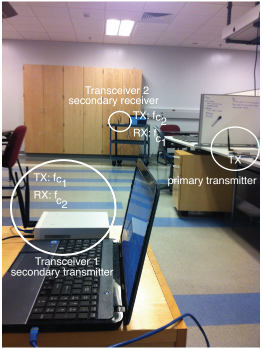
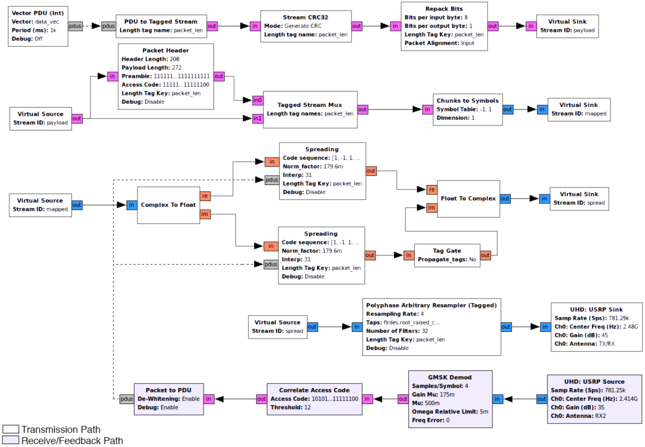
Indoor Testbed Deployment

- USRP N-210 + RFX-2400 daughtercards.
- Data channel at $f_{c_1} = 2.48$GHz.
- Control/feedback channel at $f_{c_2} = 2.42$GHz.



Transmitter Design

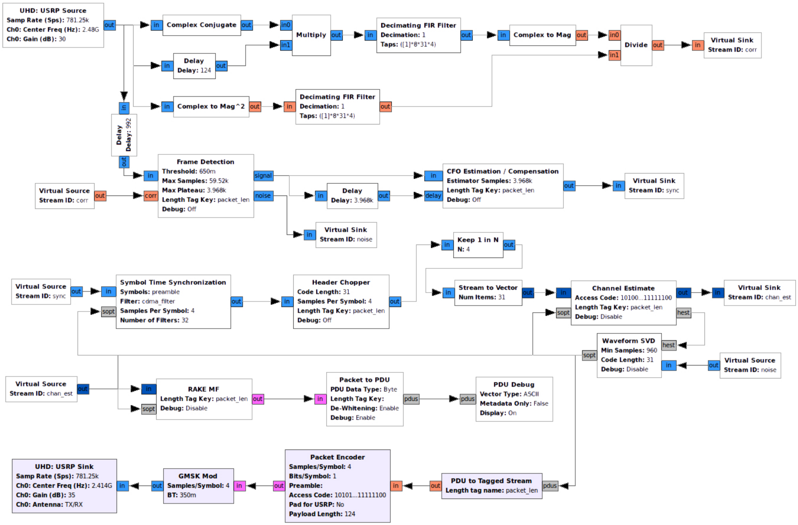
Message passing and stream tagging features exploited.



Transmitter Design (cnt'd)

- Transmitter blocks:
  - packet assembly blocks (e.g., packet header, stream CRC32).
  - burst message generator (i.e., vector pdu).
  - spreading block for modulating transmitter's bits in a waveform.
- Message passing blocks allowed us dynamic adaptation of the ST to the received optimal waveform.
- Feedback waveform is communicated by SR using already available GMSK modulation GNU Radio blocks.

Receiver Design



Receiver Design (cnt'd)

- Frame acquisition: Plateau detection based on unmodulated bits.
- CFO estimation/correction:

$$\widehat{\Delta f} = \frac{1}{2\pi L \frac{T_d}{T_s}} \angle \sum_{i=0}^{(P-1)L\frac{T_d}{T_s}-1} r[i]\, r^*\left[i + L\frac{T_d}{T_s}\right].$$

- Channel estimation:

$$\widehat{\mathbf{h}_1} = (\mathbf{S}_1^H \mathbf{S}_1)^{-1} \mathbf{S}_1^H \frac{1}{P_{AC}} \sum_{i=0}^{P_{AC}-1} \mathbf{y}_i b_1^*(P+i),$$

where $\mathbf{y}_i = b_1(P+i)\mathbf{S}_1\mathbf{h}_1 + \mathbf{p}_i + \mathbf{n}_i$, $i = 0, \ldots, J-P-1$ and $\mathbf{S}_1$ is the channel-processed code matrix.

- Maximum SINR RAKE filtering:

$$\mathbf{w}_{\text{RAKE-MVDR}} \triangleq \frac{\widehat{\mathbf{R}}^{-1}\mathbf{S}_1\widehat{\mathbf{h}_1}}{(\mathbf{S}_1\widehat{\mathbf{h}_1})^H \mathbf{R}^{-1} \mathbf{S}_1 \widehat{\mathbf{h}_1}}, \quad \widehat{\mathbf{R}} = \frac{1}{P_{AC}} \sum_{i=0}^{P_{AC}-1} \mathbf{y}_i \mathbf{y}_i^H.$$

GNU Radio Technical Details: Stream Tags/Meta-data

- Meta-data are used to tag steams of samples.
- Meta-data examples: tx_sob, tx_time, and tx_eob ⇒ Burst data transmissions with precise timing.
- PMTs can carry arbitrary amount and type of information.
- Tags are associated with samples through an absolute counter.

GNU Radio Technical Details: Asynchronous Message Passing

- Sample streams are unidirectional (downstream connections only).
- Messages can now be exchanged in both directions.
- Do not rely on buffers that operate synchronously between blocks.
- Queues used to pass messages between blocks.

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Cognitive channelization vs. fixed channelization

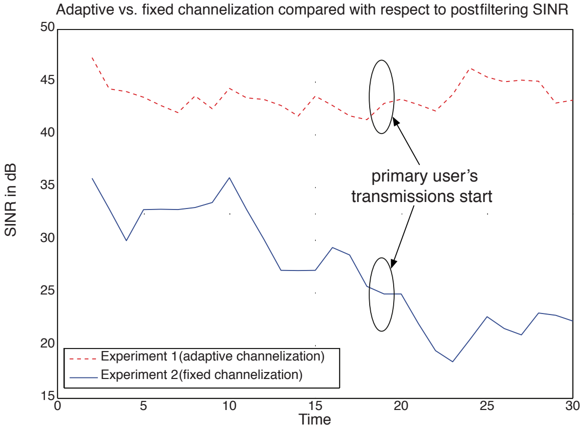

Figure : Pre-detection SINR at the secondary receiver.

Cognitive channelization vs. fixed channelization (cnt'd)

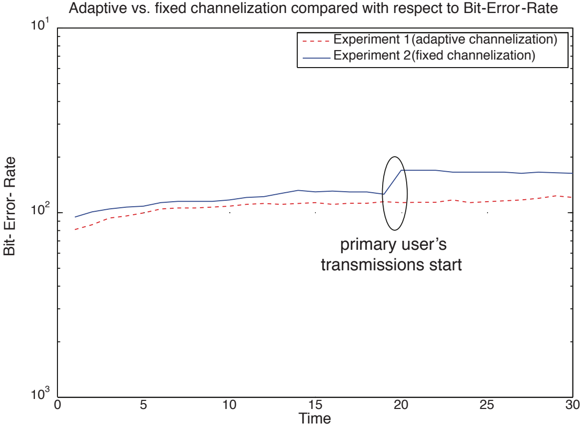

Figure : Bit-error-rate at the secondary receiver.

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Conclusions

- Designed and implemented an SDR testbed for cognitive channelization evaluation.
- Implemented a multi-user, spread-spectrum receiver, operating in a multipath fading, indoor-lab environment.
- Demonstrated optimal waveform design and channelization benefits in a three-node deployment.

THANK YOU! Questions?

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