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

George Sklivanitis, † Emrecan Demirors, ‡ Adam Gannon, †
Dimitris A. Pados, † Stella N. Batalama, ‡ Tommaso Melodia, †
and John D. Matyjas*

† SUNY at Buffalo, Department of Electrical Engineering
‡ Northeastern University, Department of Electrical and Computer Engineering
* Air Force Research Laboratory/RGIF, Rome, NY

September 17, 2014
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.
△ 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.
- \(d_k(t) = \sum_{l=0}^{L-1} s_k(l) g_T(t - lT_d)\), where \(s_k(l) \in \frac{1}{\sqrt{L}} \{\pm 1\}\).
- \(g_T(\cdot)\): SRRC pulse-shaping filter.
- \(\phi_k\): carrier phase relative to the carrier frequency \(f_c\).
Problem Formulation - Signal Model (cnt’d)

- Received baseband signal after carrier demodulation:

\[ r(t) = \sum_{i=0}^{J-1} \sum_{k=1}^{2} b_k(i) \]

\[ \times \sum_{n=0}^{N-1} h'_{k,n} d_k(t - iT - nT_d - \tau_k) e^{-j(2\pi f_c t + \gamma_k)} + n(t), \quad k = 1, 2 \]

- 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 \( \kappa_k \in \{0, 1, \ldots, L - 1\} \).
- \( n(t) \): CWGN.
Denote secondary user’s signal of interest as $b_1 H_1 s_1$. Denote cumulative interference as $p_i + n_i$. If $H_1$ is known then,

$$w_{\text{maxSINR}} = \arg \max_w \frac{\mathbb{E}\{|w^H(b_1 H_1 s_1)|^2\}}{\mathbb{E}\{|w^H(p + n)|^2\}}$$

$$= (R_p + \sigma_n^2 I_{N+L-1})^{-1} H_1 s_1$$

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

Let $R_{I+N} = R_p + \sigma_n^2 I_{N+L-1}$, then the maximum SINR attained is

$$\text{SINR}_{\text{max}} = s_1^T H_1^H R_{I+N}^{-1} H_1 s_1.$$
Now consider SINR_{max} as a function of waveform s_1.

Then,

$$s_{1}^{opt} = \arg \max_{s_1} \left\{ s_1^T H_1^H R_{I+N}^{-1} H_1 s_1 \right\}$$

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

Define

$$\tilde{M} \triangleq H_1^H R_{I+N}^{-1} H_1,$$

where q_1, q_2, \ldots, q_L denote its eigenvectors with corresponding eigenvalues \( \lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_L \).

Then, \( s_{1}^{opt} \) is the eigenvector that corresponds to the maximum eigenvalue \( \lambda_1 \).
Implementation Challenges

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

\{I&D operation will lead to SNR loss.

- No cooperation assumed between PU-SU.

- Maximal-SINR waveform design for SU ($H_1$ and $R_{I+N}$ are unknown).

- Spread-spectrum receiver design.
  - Frame Detection.
  - CFO estimation/compensation.
  - Symbol time synchronization.
  - Maximum SINR RAKE filtering.
Outline

- Motivation
- Basic Idea
- Testbed Architecture & Design
- Experimental Results
- Conclusions
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 (cnt’d)

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

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

- Channel estimation:

\[
\hat{h}_1 = (S_1^H S_1)^{-1} S_1^H \frac{1}{P_{AC}} \sum_{i=0}^{P_{AC}-1} y_i b_1^*(P + i),
\]

where \( y_i = b_1(P + i)S_1 h_1 + p_i + n_i, \) \( i = 0, \ldots, J - P - 1 \) and \( S_1 \) is the channel-processed code matrix.

- Maximum SINR RAKE filtering:

\[
\mathbf{w}_{\text{RAKE-MVDR}} \triangleq \frac{\hat{R}^{-1} S_1 \hat{h}_1}{(S_1 \hat{h}_1)^H \hat{R}^{-1} S_1 \hat{h}_1}, \quad \hat{R} = \frac{1}{P_{AC}} \sum_{i=0}^{P_{AC}-1} y_i y_i^H.
\]
Meta-data are used to tag steams of samples.

Meta-data examples: tx_sob, tx_time, and tx_eob \Rightarrow 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.
Outline

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

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

Contact: {gsklivan, pados} buffalo.edu