Karlsruhe Institute of Technology

Design and Implementation of a Cognitive Overlay System Based on FBMC

Felix Wunsch | 09/13/2017

Communications Engineering Lab

Agenda

1. The DySPAN'17 Spectrum Challenge
   - Motivation
   - Challenge Setting
   - Competing Teams
2. Our Solution
   - Phase 1: Scenario Classification
   - Phase 2: Agile SU
3. Conclusion

Spectrum Challenge: Motivation

The Spectrum Challenge is intended to benchmark...

- situational awareness
- interference mitigation techniques
- agile, high-throughput waveforms

... in a (somewhat) realistic scenario.

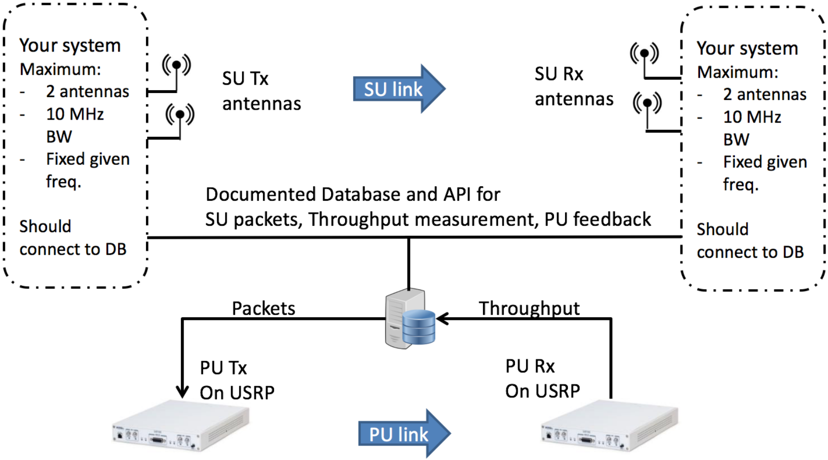
The setting:

- Contestants share the spectrum with a Primary User (PU)

The task(s):

1. Identify the transmission patterns of the Primary User (PU)
2. Design a Secondary User (SU) that optimizes its throughput without (significantly) interfering with the PU

Spectrum Challenge: Challenge Setting



Source: http://dyspan2017.ieee-dyspan.org/spectrum-challenge

Spectrum Challenge: Challenge Setting

The Primary User:

- GNU Radio based: Custom packet generator block feeding `gr-digital`'s OFDM Modulators
- Four channels with 2.5 MHz each
- Transmission pattern according to one of 10 scenarios

Scenario	Description	Inter-packet delay
0	Single random channel	5 ms
1	Single random channel	10 ms
2	Two random channels, hopping	5 ms
3	Four random channels, hopping	10 ms
4	Four channels, synchronous	5 ms
5	Two random channels, synchronous	5 ms
6	Four channels, synchronous	2 ms
7	Four channels, Poisson-distributed delays	20 ms (mean)
8	Four channels, Poisson-distributed delays	10 ms (mean)
9	Four channels, Poisson-distributed delays	5 ms (mean)

Spectrum Challenge: Challenge Setting

The two phases:

1. Situational Awareness: Detect PU scenario
   - Score: Percentage of time where estimation coincides with the actual scenario the PU is in

$$S_1 = \frac{\bar{D}}{D}, \quad \bar{D} = \text{number of correct 1ms timeslots}, \quad D = 10 \cdot 60 \cdot 10^3$$

2. Agile SU: Achieve maximum throughput while avoiding interference
   - Score: Combination of PU satisfaction and SU throughput

$$S_2 = S_{\text{PU}} \cdot T_{\text{SU}} \text{ with } S_{\text{PU}} = e^{-10 \frac{\bar{T}_{\text{PU}} - T_{\text{PU}}}{T_{\text{PU}}}}$$
$$T = \text{ Successfully delivered throughput}$$
$$\bar{T} = \text{ Offered throughput}$$

   - PU packet drops due to interference decrease the score *very* quickly

Spectrum Challenge: Competing Teams

Karlsruhe Institute of Technology

Three other contestants:

- Trinity College Dublin[1]
  - OFDM PHY (liquid DSP)
- Drexel University / Lockheed Martin[2]
  - OFDM PHY (liquid DSP)
- FORTH (Greece)[3]
  - OFDM PHY (GNU Radio)

---

[1] F. Paisana et al., ”Context-aware cognitive radio using deep learning,” 2017 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)

[2] A. Lackpour et al., ”Design and implementation of the Secondary User-Enhanced Spectrum Sharing (SUESS) radio,” 2017 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)

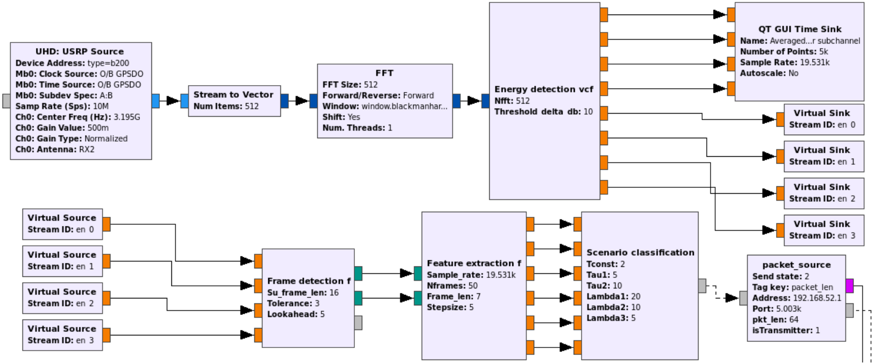
[3] S. Papadakis et al., ”An agile OFDM cognitive radio engine,” 2017 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)

Phase 1: Scenario Classification

Our approach:

1. Energy detection in each sub-band with adaptive threshold
   - Noise power measured between bands
2. Signaling of ”frame events” (start-of-frame time and sub-band index)
3. Feature extraction: Channel occupation, mean and variance of Inter-frame delay (IFD)
   - Trade-off: Feature estimation error vs. delay
4. Scenario estimation through a Decision Tree
   - Features evaluated in order of increasing error-proneness: Channel occupation $\rightarrow$ Mean IFD $\rightarrow$ IFD Variance
   - Successive identical estimations increase confidence value
5. Feedback to challenge server

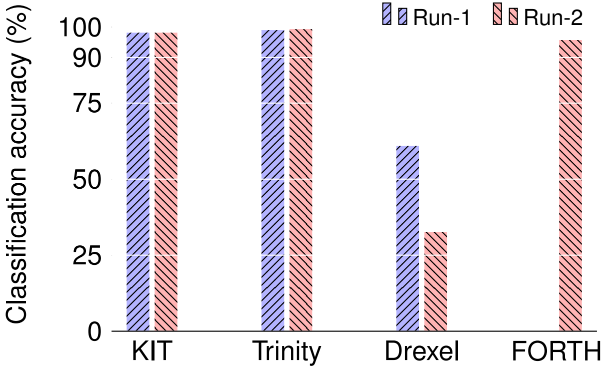
Phase 1: Scenario Classification



Scenario classification flow graph in GRC

Phase 1: Scenario Classification

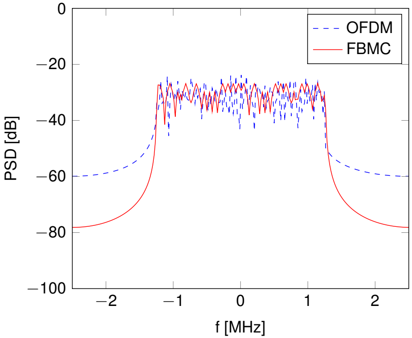
Scores: 98.14% (KIT), 99.31% (TCD), 60.93% (Drexel), 99.04% (FORTH)



Results of Phase 1 after two runs (best of two)

Phase 2: Agile SU

- Why/What is FBMC?
  - FBMC: Filter Bank Multi-Carrier
  - ”Evolved” OFDM
  - Very low out-of-band radiation due to long pulse shaping filter
- Implementation in `gr-fbmc`
  - State-of-the-art algorithms for synchronization and equalization
  - Developed at CEL, main contributors: Sebastian Koslowski, Sebastian Müller, Johannes Demel
  - Publicly available on GitHub[4]
  - Real-time capable with 20 MHz instantaneous bandwidth on a COTS laptop



[4] `https://github.com/kit-cel/gr-fbmc`

Phase 2: Agile SU

Karlsruhe Institute of Technology

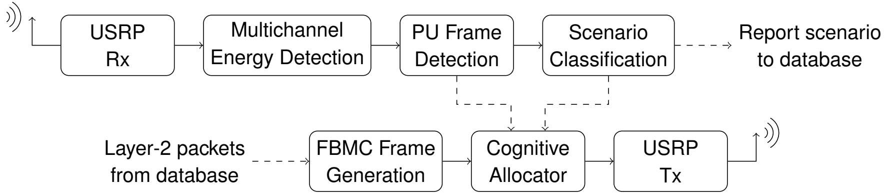
Transmitter logic:

1. Get payload data from the database and modulate sub-channel frames
   - Same sub-channel bandwidth as the PU
   - Modulated frames are buffered to reduce delay

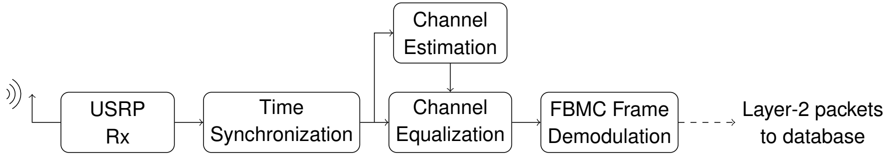
2. Cognitive Allocator identifies transmission opportunities and places frames in the time-frequency domain
   - Scenarios are continuously estimated, even during transmission
     $\rightarrow$ SU frames need to be filtered
   - Scenario serves as pattern, time alignment is done via frame events
     $\rightarrow$ RX-TX delay needs to be taken into account
   - If incoming frame events don't "match" the current scenario, the channel is temporarily blacklisted
     $\rightarrow$ Indicates scenario transition (good) or TX leakage (bad)

Phase 2: Agile SU

Block diagram of entire system:



(a) SU cognitive transmitter



(b) SU receiver

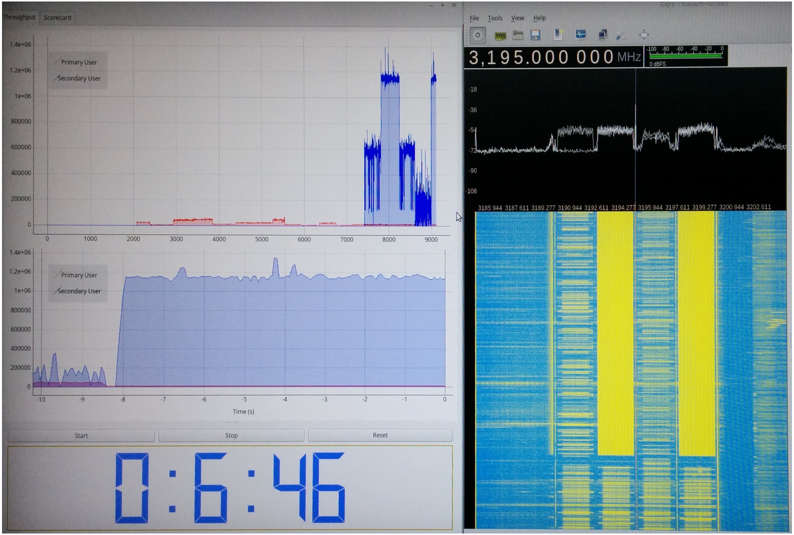
Phase 2: Agile SU

PHY configuration during the challenge:

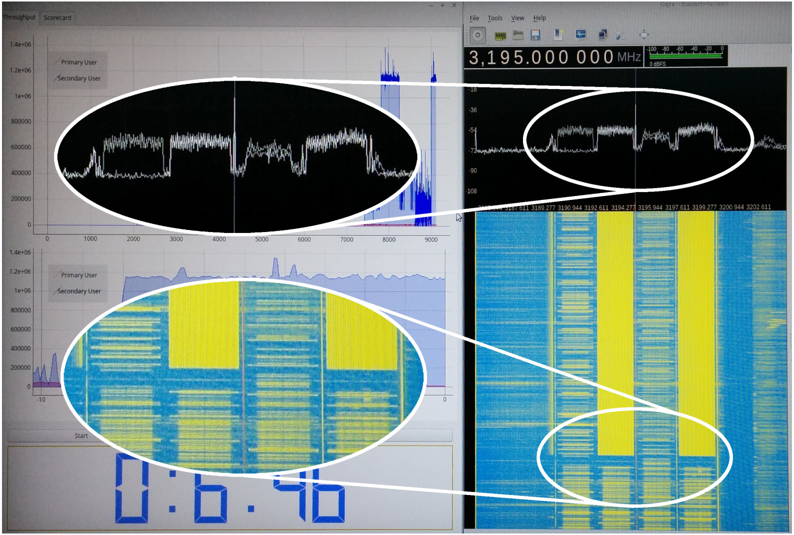
Parameter	Value
Center frequency	3195 MHz
Bandwidth	10 MHz
No. subchannels	4
No. subcarriers	128 (per subchannel)
No. used subc.	111 (per subchannel)
Modulation order	16
Payload length	768 bytes (per subchannel)
Frame length	1.7ms
Maximum throughput	13.8 Mbit/s

Maximum throughput achieved in presence of PU: about **12 Mbit/s**

Phase 2: Agile SU

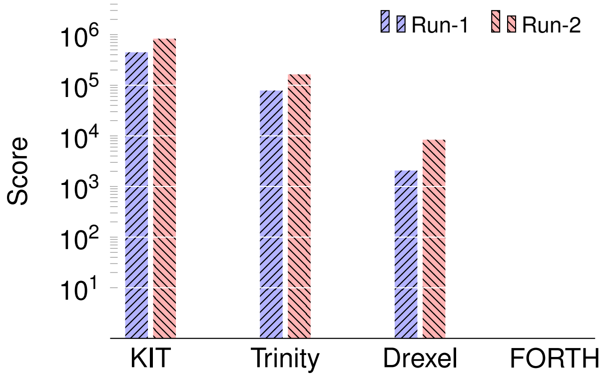


Phase 2: Agile SU



Phase 2: Agile SU

Scores: 8.31e5 (KIT), 1.64e5 (TCD), 8.39e3 (Drexel), 0 (FORTH)



Results of Phase 2 after two runs (best of two)

Conclusion

Summary

- Design of a cognitive overlay system based on FBMC
  - Performed well in both phases of the challenge
  - Virtually no interference with PU; Achieved highest score in Phase 2
  - Real-time capable on COTS laptops, no hand-tuning required
- Joint work with Sebastian Müller, Sebastian Koslowski, and Nicolas Cuervo
- Code for KIT's solution and the challenge framework is open source[6]

Outlook

- Reduce delay and improve performance by moving critical parts onto the FPGA using RFNoC
- Experiment with different classification techniques

[6] `https://github.com/networkedsystems/dyspanchallenge_2017`

Thank you for your attention!
Questions?

More information can also be found here:
"DySPAN Spectrum Challenge: Situational Awareness and Opportunistic Spectrum Access Benchmarked",
Wunsch, Paisana, Rajendran, Selim, Alvarez, Koslowski, Müller, Van den Bergh, Pollin,
in IEEE Transactions on Cognitive Communications and Networking, 2017