Leveraging Link Adaptation for Fully Autonomous and Distributed Underlay Dynamic Spectrum Access Based on Neural Network Cognitive Engine

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Outline

• Main challenges with Underlay Dynamic Spectrum Access.

• Role of Adaptive Modulation and Coding (AMC) in addressing challenges.

• A Neural Network Cognitive Engine for Autonomous and Distributed Underlay Dynamic Spectrum Access:
  » Secondary nodes infer the effect that different settings in a secondary network transmission would have on the primary network.
  » Very fine control over effects on the primary network.
A primary network (PN) owns a portion of the spectrum.

A secondary network (SN) transmits over the same portion of the spectrum.

Interference created by secondary network on primary network needs to be below a tolerable threshold.
Underlay DSA

Key challenges:

- How can SUs become aware of the interference they create on the primary network?
  - Depends on many factors, e.g.: distance between secondary transmitter and primary receiver

  \[ \gamma_i^{(p)} = \frac{G_{ii}^{(pp)} P_i^{(p)}}{\sum_{j \neq i} G_{ij}^{(pp)} P_j^{(p)} + \sum_{j=1}^{N_S} G_{ij}^{(ps)} P_j^{(s)} + \sigma^2} \]

- How to set transmit power levels in secondary transmitters that result in interference to primary links below a limit? How to set this limit?

- All done without any exchange of information between primary and secondary networks.

Solution:

- Take advantage of Adaptive Modulation and Coding (AMC) used in primary network (part of practically all high-performing wireless communications standards for more than two decades).
Adaptive Modulation and Coding

- Based on the channel SINR transmitter adapts modulation scheme and channel coding rate.

**Typical case for an LTE resource block**

Each choice of modulation scheme and channel coding rate results in one *AMC mode*, with its own Throughput vs. SINR performance curve.

Transmitter picks the AMC mode that yields best throughput subject to a limit on block error rate (BLER).
By analyzing the radio signals, it is possible through signal processing algorithms to estimate the modulation scheme being used (modulation classification).

Knowing the modulation scheme provides a broad indication of the SINR in a primary link.
Adaptive Modulation and Coding

- By analyzing the radio signals, it is possible through signal processing algorithms to estimate the modulation scheme being used (modulation classification).

- Knowing the modulation scheme provides a broad indication of the SINR in a primary link.
  
  » Knowing the full AMC mode provides a finer resolution indication.
Adaptive Modulation and Coding

• **Important property** for adaptive modulation:

When using adaptive modulation, average throughput is maintained at its maximum value as the background noise power increases to a limit value.

• In underlay DSA, the secondary network’s interference can be thought of as added background noise

\[
\gamma_i^{(p)} = \frac{G_{ii}^{(pp)} P_i^{(p)}}{\sum_{j \neq i} G_{ij}^{(pp)} P_j^{(p)} + \sum_{j=1} G_{ij}^{(ps)} P_j^{(s)} + \sigma^2}
\]
Underlay DSA – Revisiting Challenges

• How can SUs become aware of the interference they create on the primary network?
  » **Solution:** by perceiving changes in the AMC mode used at nearest primary link.

• How to set transmit power levels in secondary transmitters that result in interference to primary links below a limit? How to set this limit?
  » **Solution:** Leverage properties of AMC.

• All done without any exchange of information between primary and secondary networks.
  » **Solution 1:** Listen to nearest primary link transmission and use signal processing to infer modulation scheme
  » **Solution 2 (better):** Listen to nearest primary link transmission and infer full AMC mode (finer resolution). Realized through a cognitive engine based on a Non-linear Autoregressive Exogenous Neural Network (NARX-NN).
Cognitive Engine

- Main component to implement underlay DSA.

- Underlay DSA mechanism:
  - Sense modulation scheme of nearest primary link without transmitting. Estimate throughput and convert it to AMC mode.
  - Send a sequence of short probe messages.
  - Listen to modulation scheme used in the nearest primary link.
  - Pairs of probe message power and primary link modulation scheme are inputs to NARX-NN.
  - Output from NARX-NN are throughput estimates at nearest primary link.
  - Choose transmit settings that meet a maximum allowed reduction in throughput at the nearest primary link.
NARX Neural Network

- Sequence of transmit powers for secondary probe messages
- Sequence of corresponding modulation schemes at nearest primary link
- Previous throughput predictions

Predict AMC throughput
Training the NARX-NN

For a network setup, a sequence of secondary transmit powers yields a range of SINR values.

NARX-NN learns the approximate location of the SINR band through the input of modulation schemes.

\[ \gamma_{i}^{(p)} = \frac{G_{ii}^{(pp)} P_{i}^{(p)}}{\sum_{j \neq i} G_{ij}^{(pp)} P_{j}^{(p)} + \sum_{j=1}^{N_S} G_{ij}^{(ps)} P_{j}^{(s)} + \sigma^2} \]
Training the NARX-NN

MARX-NN learns to predict throughput (equivalently the modulation scheme and channel coding rate)

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\[
\gamma_{i(p)} = \frac{G_{i(p)}^{(pp)} P_{i(p)}^{(p)}}{\sum_{j \neq i} G_{i(p)}^{(pp)} P_{j(p)}^{(p)} + \sum_{j=1}^{N_S} G_{i(p)}^{(ps)} P_{j(s)}^{(s)} + \sigma^2}
\]
Training the NARX-NN

A different network setup, yields a different range of SINR values with new range of throughput predictions.
Eventually, after training with many different network scenarios, the NARX-NN cognitive engine learns the throughput vs SINR AMC performance curve and the corresponding modulation schemes used.
Results

- Primary network has 25 access points located in a 5x5 square grid that wraps around the edges.
  - Access points are at the center of a square 200x200 m. coverage area.
  - Each access point is connected to one primary transmitter located at random within the square coverage area.

- Not all 25 primary transmitters are active in a transmission. The ratio of number of active transmitters to total number of transmitters is the **network load**.
- Four secondary receivers placed at random within the primary network coverage area.
- Each secondary transmitter placed at random within no more than 50 m. of its assigned receiver.
- Primary transmit power between -20 and 40 dBm. Secondary transmit power between -20 and 30 dBm.
Results

Average throughput and relative throughput change in primary network
Results

Average throughput and relative throughput change in primary network

Relative throughput change in primary network as a function of background noise power
Results

Average throughput in secondary network
Results

AMC mode prediction accuracy (in terms of Channel Quality Indicator – CQI)
Conclusions

• Presented a neural network cognitive engine for autonomous and distributed underlay dynamic spectrum access:

  » A cognitive engine based on a NARX neural network leverages the use of adaptive modulation and coding (AMC) in the primary network to infer the effect that different settings in a secondary network transmission would have on the primary network.

  » No exchange of information between primary and secondary network.

  » The technique is able to accurately predict the full AMC mode used in a primary link.

  » Very fine control over effects on the primary network:

    » The cognitive engine is able to find transmit settings for the cognitive radio so that average throughput at the primary network is not reduced by more than a chosen limit.