Fundamental Limits of Networks with Cognitive Users

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Goals

- Propose channel models that capture cognitive radio network characteristics:
  1) Have both primary and secondary users
  2) Secondary users have more capabilities such as
     - Sense the environment efficiently
     - Can decode information from detected signals
     - Extra power, multiple antennas
- Use an information-theoretic approach to evaluate performance
  - Derive achievable rates
  - Derive outer bounds
  - Present scenarios for which the capacity results can be obtained

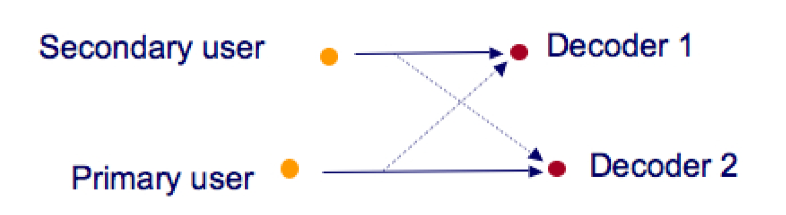
- How can the senders improve their rates?

→ Propose cooperative strategies:
  - Based on the capabilities of the cognitive users
  - Primary users can be oblivious of the secondary users or
  - Decide to cooperate
  - Secondary users may be required to limit their transmissions such that they do not reduce the rates of primary users
  - This limits operation to a specific point of the capacity region

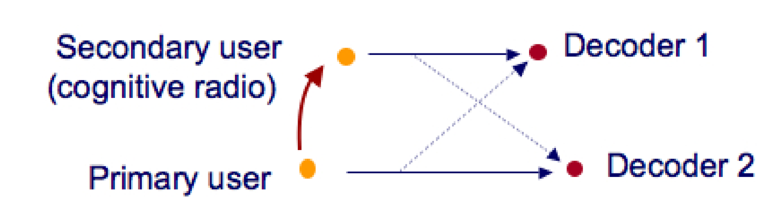
Considered Cognitive Radio Settings

- Consider two-transmitter, two-receiver network:

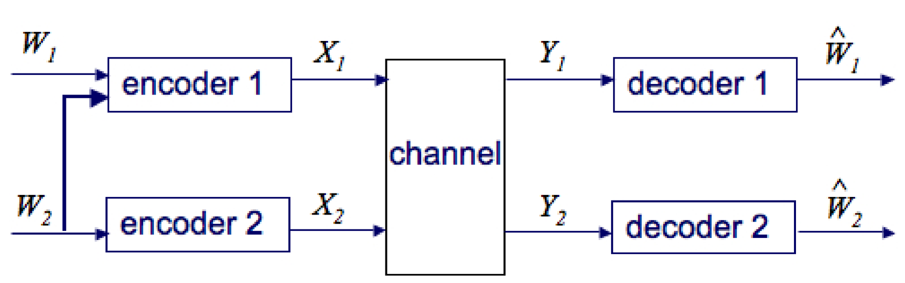
⇒ Interference channel model
  - Capacity region unknown
  - Senders are unaware of each other's messages
  - Signals transmitted at one sender ignored at the other



- Cognitive radio network: One transmitter is a cognitive radio
  - It can "overhear" transmission of the primary user
  - It obtains *partially* the primary user's message ⇒ it can cooperate



Idealized Model

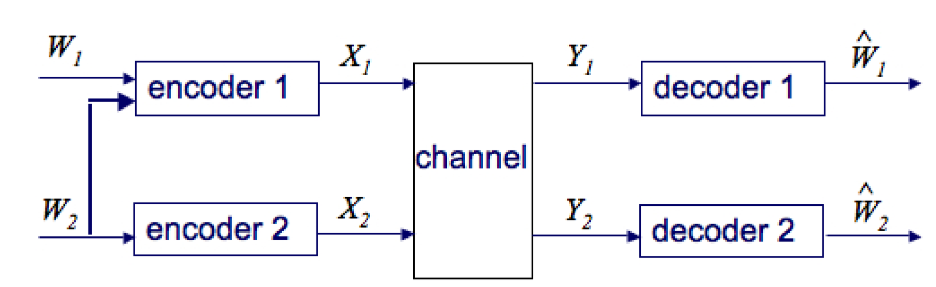


- Secondary user learns the full message W_2
- Encoding functions: $\mathbf{x}_1 = f_1(W_1, W_2)$, $\mathbf{x}_2 = f_2(W_2)$
- Decoding functions: $\hat{W}_1 = g_1(\mathbf{Y}_1)$, $\hat{W}_2 = g_2(\mathbf{Y}_2)$
- The error probability $P_e = \max\{P_{e,1}, P_{e,2}\}$
  for $P_{e,t} = P[g_t(\mathbf{Y}_t) \neq W_t]$ $t = 1,2$

Prior work:

- Cognitive Radio Channel *[Devroye, Mitran, Tarokh, 2004]*
  - Derived an achievable rate region
- The Interference Channel with Unidirectional Cooperation *[Marić, Yates & Kramer, 2005]*
  - Showed capacity in strong interference
- The Interference Channel with Degraded Message Set *[Wu, Vishwanath & Arapostathis, 2006]*
  - Showed capacity for weak interference and Gaussian channels in weak interference
- Cognitive Radio Channel *[Jovičić& Viswanath, 2006]*
  - Showed capacity for Gaussian channels in weak interference

Ongoing Work: Interference Channel with Unidirectional Cooperation



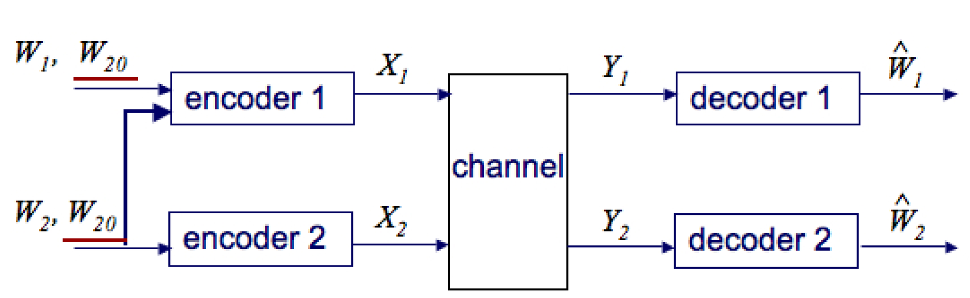
- We derived a new achievable rate region:
- The coding strategy employs:
  - Rate-splitting to reduce the interference at the receivers
  - Coding techniques for channels with states non-causally known to the transmitter
- We demonstrated the scheme for Gaussian channels
- The proposed coding strategy improves on the previously proposed schemes

- Outer bounds:
  1) We derived a general outer bound that is based on the Nair-El Gamal outer bound on the broadcast channel capacity
     - It has the same form as Nair&El Gamal bound
     - The difference is in the factorization of the input distribution reflecting the fact that only one-way cooperation is possible
  2) We derived a general outer bound that holds if

     $$I(X_1;Y_1 \mid X_2) \le I(X_1;Y_2 \mid X_2)$$

     - When the condition is satisfied, decoder 2 experiences strong interference, i.e., it can decode W_1 with no rate penalty

Ongoing Work: Interference Channel with Partial Cooperation



- Secondary user overhears message W_2 as it is transmitted

  ⇒ It can only use it in the next encoding block
  - Encoder 2 uses Block Markov Encoding
- As a consequence:

  At each time, secondary user has partial information about what is currently being sent at primary user
  - Common part at time i: $W_2[i-1]$

- We model this as a common message at two transmitters

- The encoding scheme devised for the full cooperation can be generalized for the partial cooperation case
- We derived the general outer bounds on the capacity of this channel
- We determined the capacity region in the strong interference:
- *Theorem:* An interference channel with partial cooperation that satisfies

$$I(X_1;Y_1 \mid X_2) \le I(X_1;Y_2 \mid X_2)$$
$$I(X_2;Y_2 \mid X_1) \le I(X_2;Y_1 \mid X_1)$$

for all product input distribution $p(x_1)p(x_2)$ and

$I(X_1,X_2;Y_2) \le I(X_1,X_2;Y_1)$ for all $p(x_1,x_2)$ has capacity region

$$\begin{aligned} C = \bigcup \{ & (R_0,R_1,R_2) : R_0 \ge 0, R_1 \ge 0, R_2 \ge 0 \\ & R_1 \le I(X_1;Y_1 \mid X_2,U) \\ & R_2 \le I(X_2;Y_2 \mid X_1,U) \\ & R_1 + R_2 \le I(X_1,X_2;Y_1 \mid U), I(X_1,X_2;Y_2 \mid U) \\ & R_0 + R_1 + R_2 \le I(X_1,X_2;Y_2) \} \end{aligned}$$

where the union is over $p(u)p(x_1 \mid u)p(x_2 \mid u)p(y_1,y_2 \mid x_1,x_2)$

Future Work: More Realistic Models, Large Networks and Simple Schemes

- Presented achievable rate region and the outer bound are next to be evaluated and compared for Gaussian interference channels with unidirectional cooperation
  - Scenarios for which the bounds are tight are to be identified if possible
  - Channel models that take into account the delay at the cognitive transmitter in obtaining the message of the primary user are to be considered
- Based on the results, the operating points for the networks with cognitive users such as encoding schemes, power and bandwidth allocation are to be characterized
- Results are to be generalized to large networks with cognitive users
  - Simple encoding schemes for such networks need to be devised
- Different scenarios will be considered:
  - When primary users are oblivious of the secondary users
  - When primary users can help transmission of the secondary users
- Channel models that are tractable and that incorporate additional characteristics of cognitive radios such as multiple antennas or extra power are to be developed