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Energy Detection in Full-Duplex Cognitive Radios under Residual Self-interference

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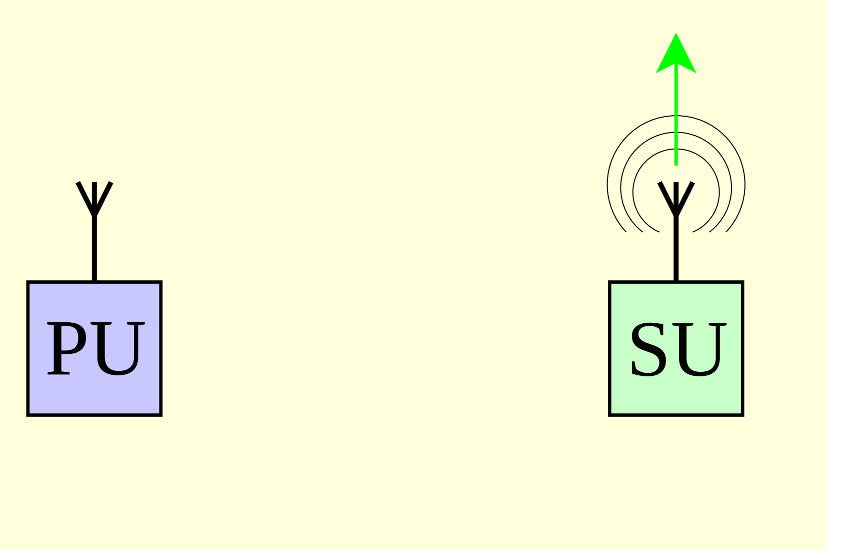
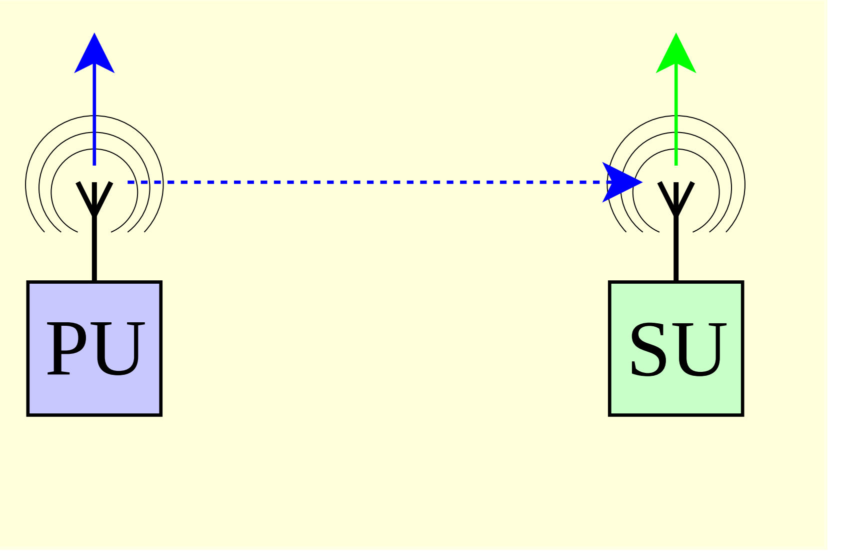
Introduction

Overlay Cognitive Radio Systems



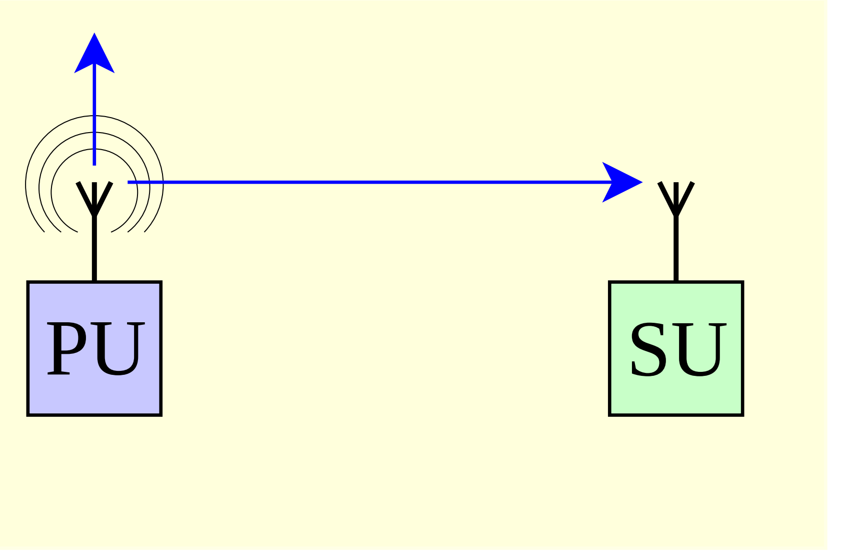
- A secondary user (SU) may use a frequency band if all nearby primary users (PUs) are inactive
- PUs' transmission schedule is unknown to SUs
- A cognitive radio adapts dynamically to PUs' state
    - ▷ the hidden/exposed node problems not considered herein

Spectrum Sensing



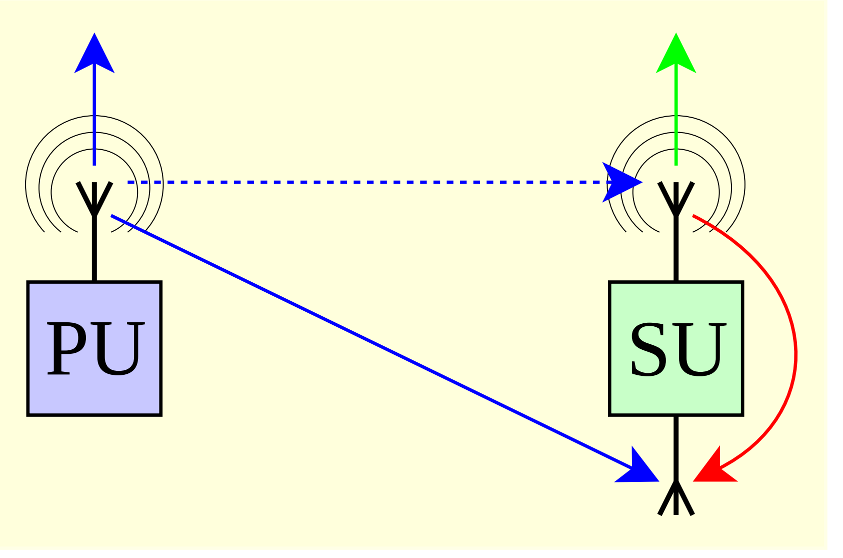
- The SU needs to back off from transmitting if a PU becomes active
  - ▷ collisions considered very harmful
- Cooperative sensing by other SUs at the cost of overhead
  - ▷ spectrum allocation and transmission energy for feedback

Half-Duplex Secondary User



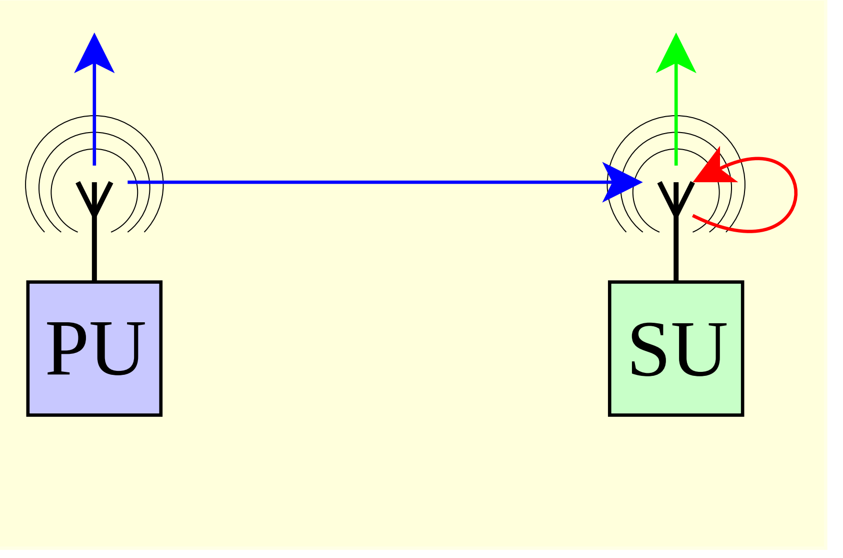
- The half-duplex constraint: conventional cognitive radios take sensing breaks for detecting whether a PU has become active
  - ▷ lost transmission opportunities during sensing
  - ▷ risk of undetectable collisions during transmission

Full-Duplex Secondary User



- Modern full-duplex wireless radio transceivers will be capable of simultaneous spectrum sensing and transmission
  - ▷ residual self-interference after imperfect cancellation
- Two-antenna implementation for high(er) physical isolation (but there is still only one transmitter–receiver pair in the SU!)

Single-Antenna Full-Duplex Secondary User



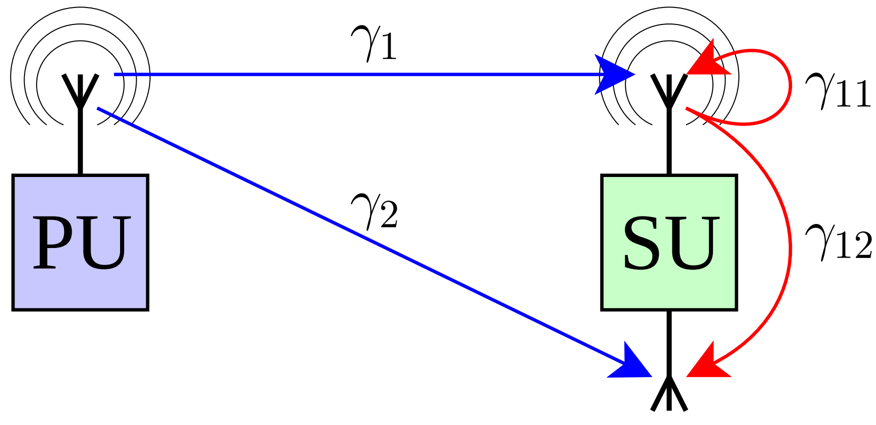
- Also single-antenna full-duplex radio transceivers may eventually become viable or, even, preferable
  - ▷ the same antenna is used for sensing and transmission
- It is reasonable to presume that the level of residual distortion will be higher than with the two-antenna implementation

Scope and Objectives

- Scope: energy detection for spectrum sensing in full-duplex cognitive radios in the presence of residual self-interference
  - ▷ reference case: switching between sensing and transmitting in conventional half-duplex cognitive radios
- Research questions
  1. How does the additional distortion decrease the probability of detecting PU transmission and could the effect be compensated by using a longer integration period?
  2. What happens when a full-duplex SU aims to detect PU activity through a different channel than a half-duplex SU?
  3. How does two-antenna full-duplex SUs compare with single-antenna SUs?

System Model

Channel Signal-to-Noise Ratios (SNRs)



- Feedforward channels: $\gamma_1 \triangleq \frac{h_1^2 E_x}{\sigma_1^2}$ and $\gamma_2 \triangleq \frac{h_2^2 E_x}{\sigma_2^2}$
  - ▹ Thermal noise: $\mathcal{E}\{n_1^2(t)\} \triangleq \sigma_1^2$ and $\mathcal{E}\{n_2^2(t)\} \triangleq \sigma_2^2$
- Feedback channels (residual self-interference): γ_{11} and γ_{12}
  - ▹ Distortion noise: $\mathcal{E}\{d_{11}^2(t)\} \triangleq \gamma_{11}\sigma_1^2$ and $\mathcal{E}\{d_{12}^2(t)\} \triangleq \gamma_{12}\sigma_2^2$

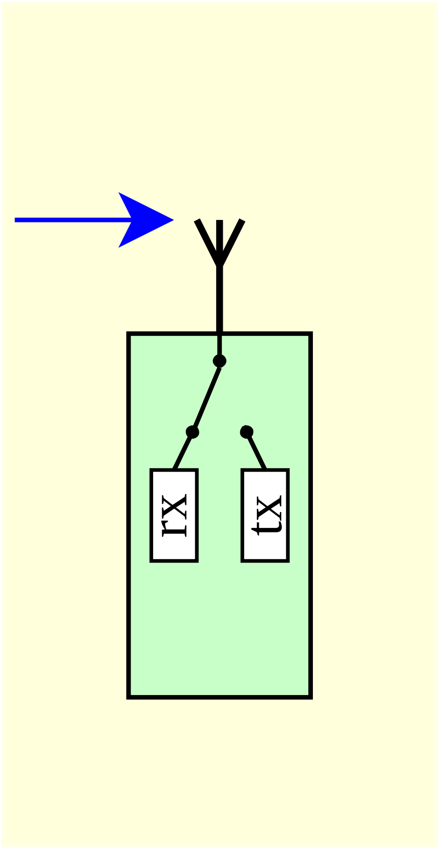
Single-Antenna Half-Duplex (HD) Transceiver

- A PU is active and transmitting an unknown deterministic signal $x(t)$ for which $\int_{t_0}^{t_0+T} x^2(t)\,\mathrm{d}t \triangleq E_x$
- A half-duplex SU is not able to receive during transmission
- Received signal during a sensing break:

$$y_1(t) = h_1\, x(t) + n_1(t)$$

- The receiver SNR:

$$\gamma_{\mathrm{HD}} = \gamma_1 \qquad (2)$$



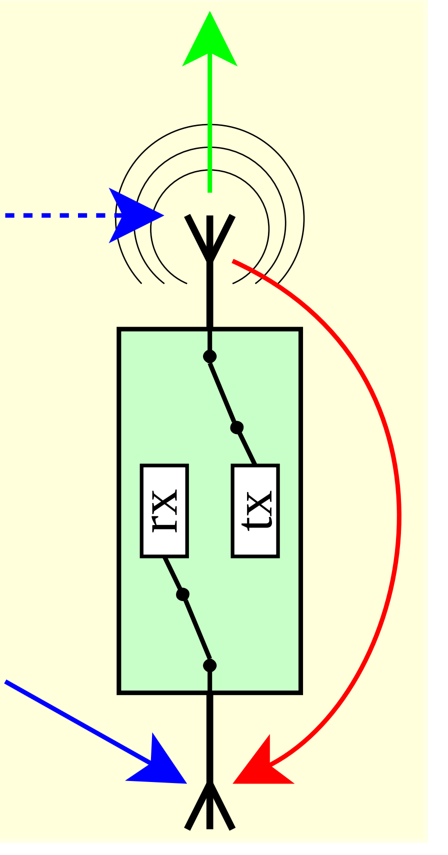
Two-Antenna Full-Duplex (FD2) Transceiver

- A full-duplex SU is capable of simultaneous sensing and transmission
  - ▷ A baseline device has two antennas
- Self-interference cancellation is necessary but likely imperfect
- Received signal with residual distortion:

$$y_2(t) = h_2\, x(t) + d_{12}(t) + n_2(t)$$

- The receiver SNR:

$$\gamma_{\mathrm{FD2}} = \frac{\gamma_2}{\gamma_{12} + 1} \qquad (4)$$



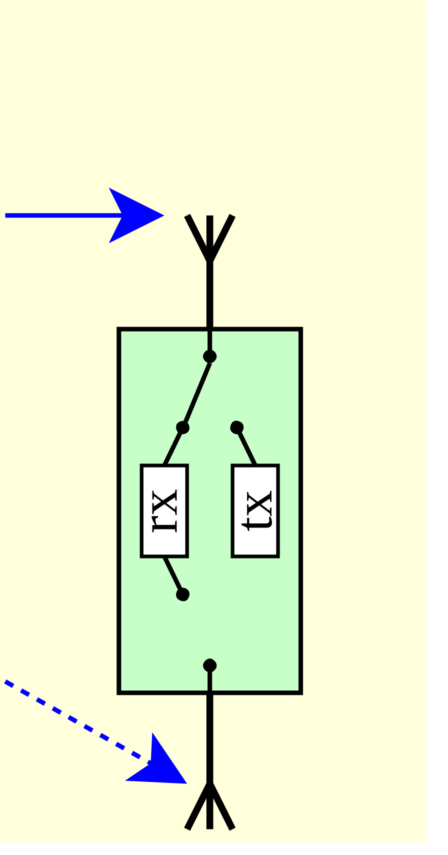
Two-Antenna Half-Duplex Operation

- The two-antenna full-duplex SU may operate like the half-duplex SU when it is not transmitting
  - ▷ extra switches are needed though
- No (residual) self-interference
- Received signal without transmission:

$$y_1(t) = h_1\, x(t) + n_1(t)$$

- The receiver SNR:

$$\boxed{\gamma_{\mathrm{FD}} = \gamma_1}$$



Single-Antenna Full-Duplex (FD1) Transceiver

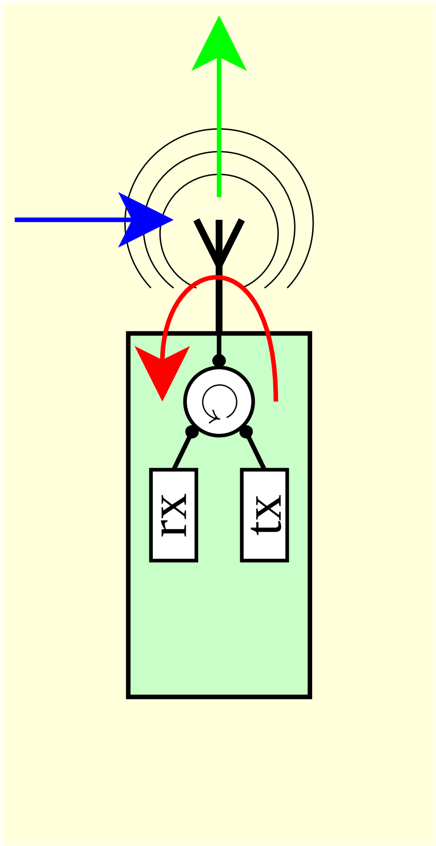
- A single-antenna full-duplex device uses a circulator for connecting its transmitter and receiver to the same antenna
- Received signal with residual distortion:

$$y_1(t) = h_1\, x(t) + d_{11}(t) + n_1(t)$$

- The receiver SNR:

$$\boxed{\gamma_{\mathrm{FD1}} = \frac{\gamma_1}{\gamma_{11} + 1} \qquad (6)}$$

- The single-antenna full-duplex SU becomes equivalent to the half-duplex SU when it is not transmitting ($\gamma_{11} = 0$)



Energy Detection under Residual Self-interference

Receiver Operating Characteristics

- Letting H_0 and H_1 refer to the respective hypotheses of signal absence and presence, the received signal can be modeled as

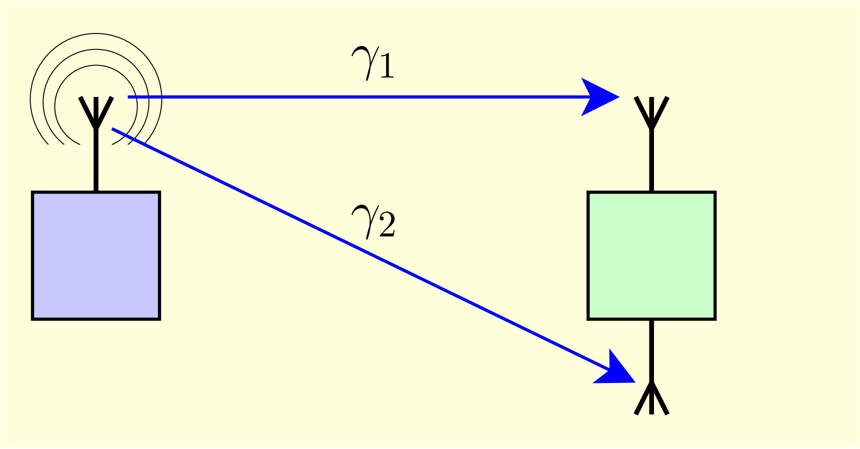
$$y(t) = \begin{cases} d(t) + n(t), & H_0 \\ d(t) + n(t) + h\,x(t), & H_1 \end{cases}$$

- Decision variable for energy detection: $Y = (2/N_0) \int_{t_0}^{t_0+T} y^2(t)\,\mathrm{d}t$
- With $u = T \cdot W$, the probability of false alarm and the probability of missed detection:

$$P_\mathrm{f} \qquad = \Pr(Y > \lambda | H_0) = \frac{\Gamma\left(u, \frac{\lambda}{2}\right)}{\Gamma(u)}$$

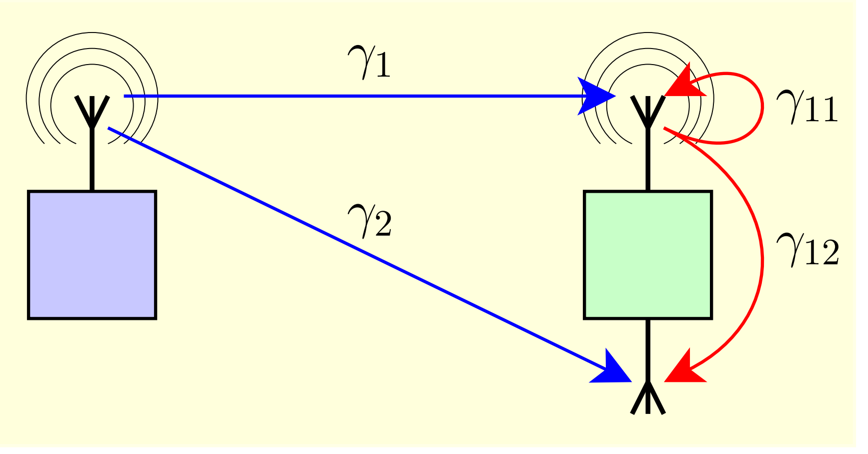
$$P_\mathrm{m}(\gamma) = \Pr(Y \leq \lambda | H_1) = 1 - Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right)$$

Sensing when the SU is *not* transmitting



- The probability of missed detection
  - FD2: $P_{\mathrm{m}}(\gamma_2)$ (or $P_{\mathrm{m}}(\gamma_1)$)
  - HD and FD1: $P_{\mathrm{m}}(\gamma_1)$
- The probability of false alarm P_{f} is the same for all the SU variations, irrespective of whether the full-duplex SU transmits during sensing or not

Sensing when the SU *is* transmitting

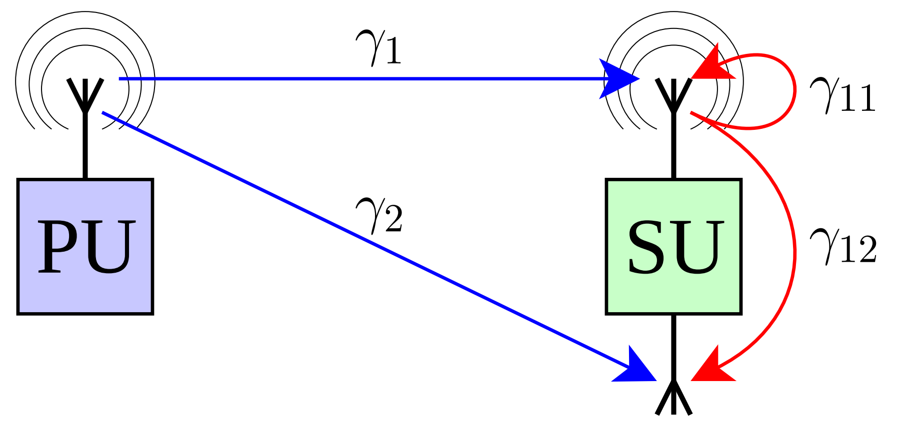


- The probability of missed detection
  - FD2: $P_\mathrm{m}(\gamma_\mathrm{FD2}) = P_\mathrm{m}\left(\frac{\gamma_2}{\gamma_{12}+1}\right)$
  - FD1: $P_\mathrm{m}(\gamma_\mathrm{FD1}) = P_\mathrm{m}\left(\frac{\gamma_1}{\gamma_{11}+1}\right)$
- The half-duplex SU cannot sense while transmitting
  - HD: $(P_\mathrm{f}, P_\mathrm{m}) = (?, 1)$ (but $P_\mathrm{m}(\gamma_1)$ during a sensing break)

Numerical Results

Example System Parameters

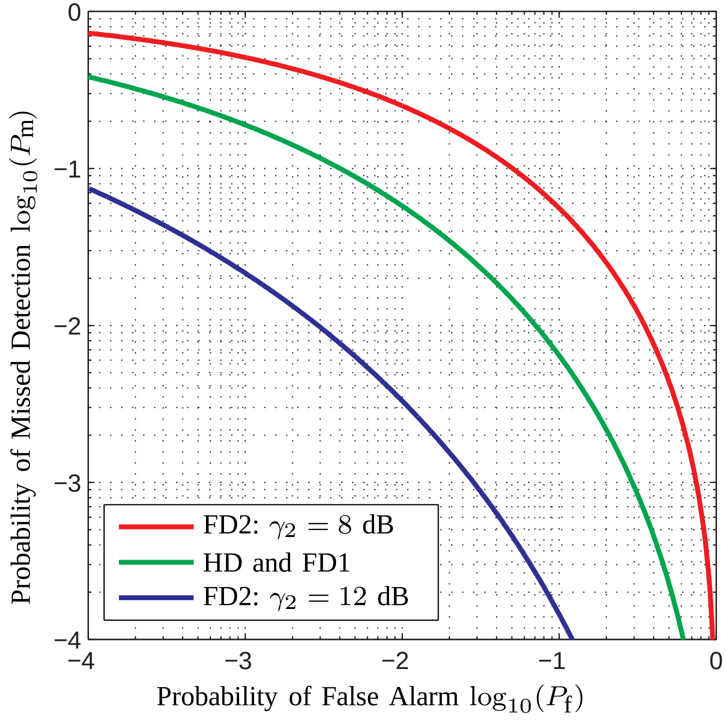
- Unless otherwise specified, the channel gains are
  - $\gamma_1 = 10$ dB
  - $\gamma_2 \in \{8, 12\}$ dB
  - $\gamma_{11} = 10$ dB
  - $\gamma_{12} = 6$ dB



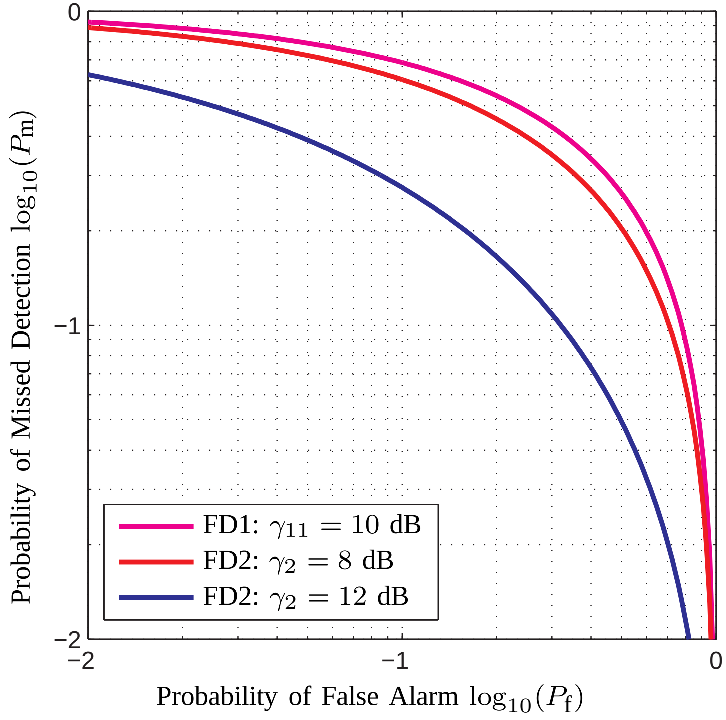
- The time–bandwidth product is chosen as
  - $u = 1$

Receiver Operating Characteristics (ROC)

(a) only sensing:

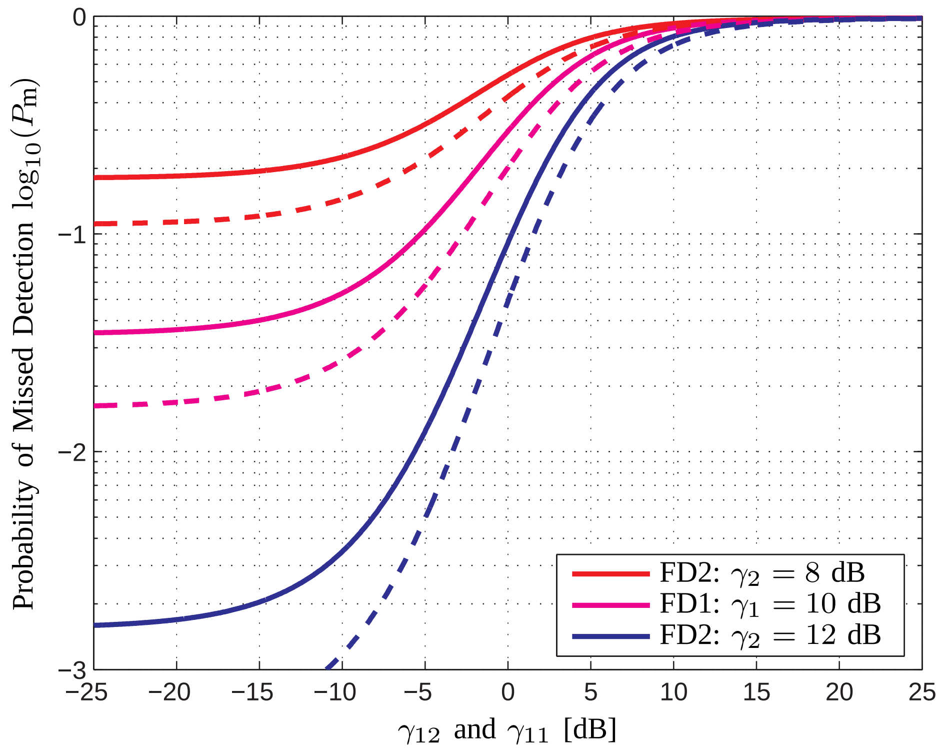


(b) simultaneous transmission and sensing:



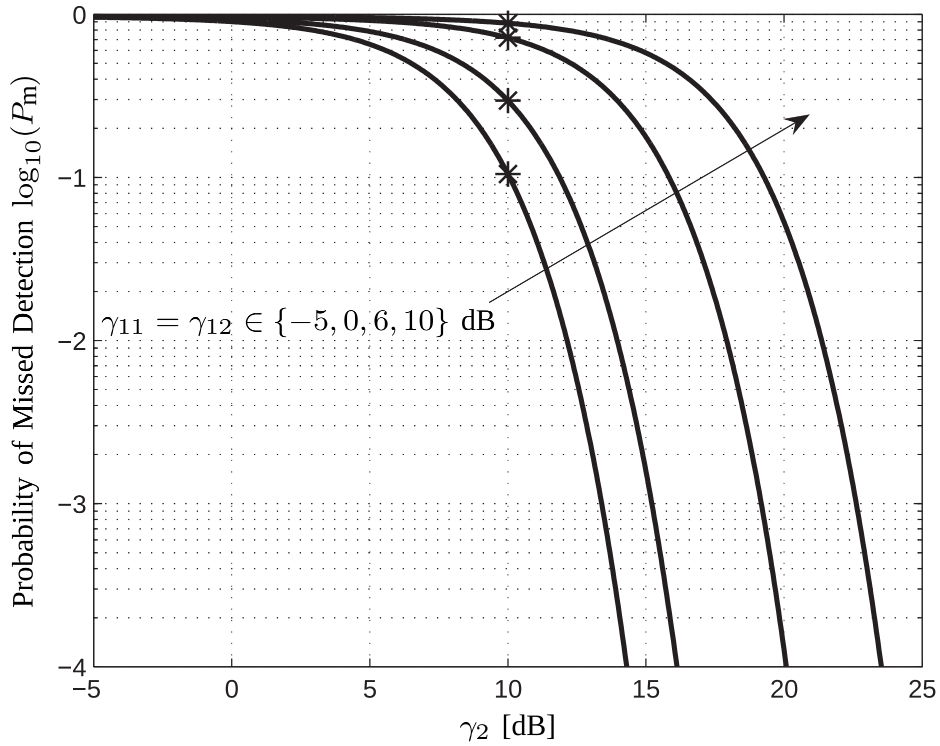
- The probability of false alarm and the probability of missed detection are increased by more than one magnitude when the SU begins to transmit while sensing ($P_\mathrm{m}(\gamma_\mathrm{HD}) < P_\mathrm{m}(\gamma_\mathrm{FD2}) < P_\mathrm{m}(\gamma_\mathrm{FD1})$)

Detection Performance ($P_\mathrm{f} = 2\%$) vs. Self-interference



- The half-duplex SU achieves $P_\mathrm{m} = 3.5\%$ if it is only sensing
- The effect of residual self-interference could be compensated by using a longer integration period in energy detection

Detection Performance ($P_\mathrm{f} = 2\%$) vs. Gain Imbalance



- A fortunate two-antenna SU may even be able to detect PU activity with a higher probability, and gain imbalance can also effectively attenuate residual self-interference

Conclusion

Conclusion

- Scope: basic energy detection for spectrum sensing in overlay cognitive radio systems
- Focus: full-duplex wireless radio transceivers that are capable of simultaneous sensing and transmission
  - ▷ Pro: avoiding the overhead of conventional sensing
  - ▷ Con: residual self-interference after imperfect cancellation
    - – the effect can be reduced by extending sensing period
- Two full-duplex implementations compared with conventional half-duplex sensing
  - ▷ single-antenna full-duplex transceiver
    - – higher residual distortion level
  - ▷ two-antenna full-duplex transceiver
    - – a channel gain imbalance problem

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