On Reliable Communication over RF and Optical Wireless Channels

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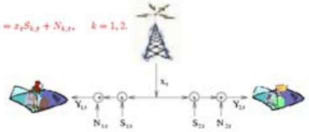
Problem Setting: Time Varying RF Channels

- In several situations, the transmitters and receivers in a communication network, or the sensors and actuators in a control system, must operate without a complete knowledge of the probability law which governs the transmission channel, for instance, when the probability law changes with time.
- Examples include those arising in RF mobile wireless communication:
  - cellular phone network;
  - indoor network of mobile sensors and actuators.
- Owing to the mobility of the transmitters and receivers, or changing physical environments, the degradation of the transmitted signals due to multipath, shadowing and propagation losses, is time-varying.
- The time-varying behavior of the channel probability law is typically described in terms of the evolution of an underlying channel state characterizing the "condition" of the channel.
- Varying extents of channel state information (CSI) can often be provided to the transmitters or receivers, leading to better communication.

Time-Varying RF Broadcast Channel

$Y_{k,t} = x_t S_{k,t} + N_{k,t}, \quad k = 1, 2.$



- Downlink of a mobile wireless channel: *time-varying fading broadcast channel.*
- Time-varying behavior modeled by introducing a channel *state* $S_t = (S_{1,t}, S_{2,t})$.
- Knowledge of the state at transmitter or receivers can lead to higher "throughputs."
- Key Objective: To study how CSI can be gainfully used in devising transmitter and receiver strategies so as to enable reliable and efficient communication over time-varying RF channels.

Problem Setting: Combining RF and Optical Transmissions

- With the crowding of the RF spectrum and increasing demand for bandwidth availability, recent proposals recommend the use of optical wireless links as a viable complement.
- Switching between RF and optical modes also affords a means of sending additional information ("sum channel").
- We are currently investigating the combined use of wireless RF and optical links.
- Key Objective: To understand how RF power control can be combined with RF/optical link-switching to achieve higher throughputs.

Some Specific Problems

- Capacity regions of broadcast or downlink time-varying RF channels when various degrees of channel state information (CSI) are available to the transmitter or receivers.
  - For all problems, we assume that each receiver has perfect local CSI.
- Special cases:
  - CSI ordering at the transmitter and receivers.
    - Capacity region.
  - No CSI at the transmitter. ⇐
    - Inner and outer bounds.
  - Perfect CSI at the transmitter, and (possibly) CSI ordering at the receivers.
    - Conditional Gaussianity is lost.

Fading Broadcast Channel without Transmitter CSI

Two-receiver fading broadcast channel (slow, flat fading channel): At receiver-k, $k = 1, 2$:

$$Y_{k,t} = x_t S_{k,t} + N_{k,t}, \quad t \geq 1,$$

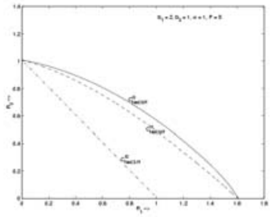
where

- $\{x_t\}$ is the $\mathbb{R}$-valued transmitted signal with average power P;
- $\{S_{k,t}\}$ is the $\mathbb{R}^+$-valued fade suffered by the transmission to receiver-k;
- $\{N_{k,t}\}$ is i.i.d. Gaussian noise $\sim \mathcal{N}(0, \sigma^2)$ at receiver k.
- Transmitter has no CSI while each receiver-k has perfect local CSI.

We have derived the following inner and outer bounds on the capacity region.

- Outer bound C^O is obtained by providing CSI ordering at the transmitter and receivers.
- Inner bound $C^I = co(C_1^I \bigcup C_2^I)$, where $C_k^I \sim$ receiver-k decodes both messages, receiver-k^c decodes only its own message.

Example: Rayleigh Fading Broadcast Channel



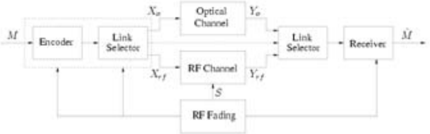
- I.i.d. Rayleigh fading:

$$f_{S_k}(x) = \frac{x}{b_k^2} \exp(-\frac{x^2}{2b_k^2}), \quad x \geq 0, \quad k = 1, 2.$$

- Gap between inner and outer bounds:

$$C_2^I \subset C_1^I = C^I \subset C^O.$$

Combining RF and Optical Transmissions



- RF fading link: $F_{Y_{rf}|X_{rf},S} \sim \text{Gaussian}(sx_{rf}, \sigma_N^2)$.
- Optical link: $F_{Y_o|X_o} \sim \text{Poisson}(x_o + \lambda_d)$.
- Input constraints:
  - Average power constraint for the RF link.
  - Average and peak power constraints for the optical link.
  - Constraint to limit use of optical link.

Combined RF/Optical Channel Model

- Discrete time model for the switching channel.
  - At each time, the channel selector selects one of the two available channels.
  - The decision V depends on RF channel fade information S.
  - Randomness in switching decision contributes to additional information.
- Combined channel transfer function:

$$W^n(y^n|x^n, s^n, v^n) = \prod_{t:v_t=1} W_{rf}(y_t|x_t, s_t) * \prod_{t:v_t=0} W_o(y_t|x_t).$$

- Input constraints:
  - Peak power constraint for optical channel:

$$0 \leq x_t \leq A \quad \forall t : v_t = 0.$$

  - Average power constraint for the combined channel:

$$\frac{1}{n} \sum_{t=1}^{n} E[X_t^2 1(V_t) + X_t 1(\bar{V}_t)] \leq P.$$

  - Constraint on overuse of optical channel.

Planned Work

- Downlink of mobile wireless channel
  - *Adequate* CSI at the transmitter and receivers: power-control across transmit antennae and beamforming ?
  - *No* CSI: Space-time coding ?
  - *Partial* CSI: Intermediate solutions ?
- Determination of capacity formula for the combined RF/optical channel
  - RF/optical "link-switching"
    - "Sum channel" with constraints: transmission of additional information.
    - Relationship to RF power control.
  - Combined use of RF/optical fading links.