# RELIABLE COMMUNICATION
# OVER
# RF AND OPTICAL 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.

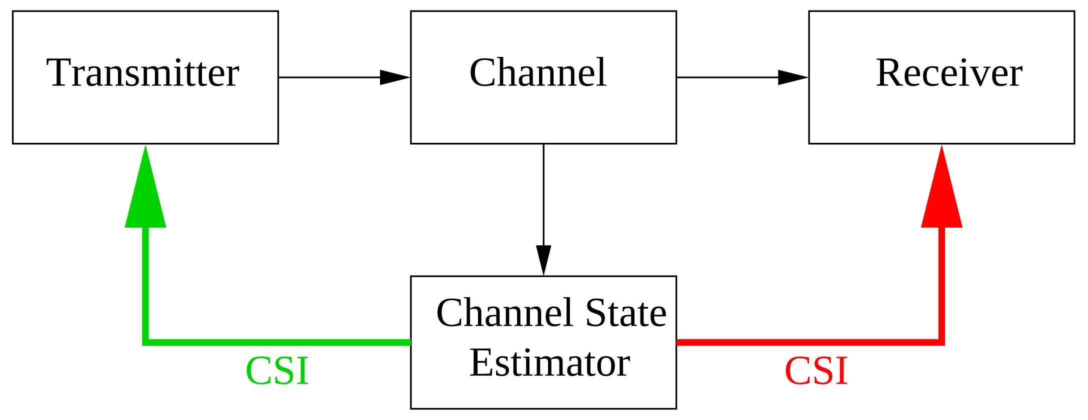
- Examples include those arising in RF mobile wireless communication:
  - cellular phone network;
  - RF network of command posts, soldiers and equipment;
  - indoor network of mobile sensors and actuators.

- 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.

# Channel State Information

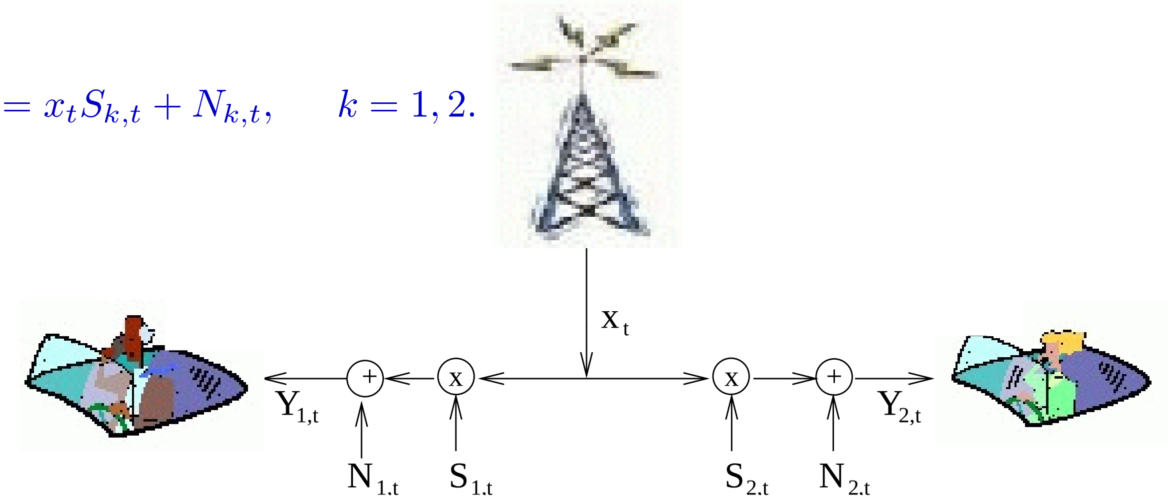
- The time-varying behavior of the channel probability law is typically described in terms of the evolution of an underlying channel state characterizing the "condition" of the channel.

- Varying extents of channel state information (CSI) can often be provided to the transmitters or receivers, leading to better communication.



# Time-Varying RF Channel

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



- 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."

# 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.

# Problem Setting: Optical Fading Channel - Model, Receiver Structure

- In free-space optical communication, atmospheric turbulence effects, i.e., random fluctuations in the refractive index at optical wavelengths, give rise to optical fading.
- Our study focuses on receiver structures for estimating fading coefficients and optimal signal detection.
- This will be incorporated into our study of combined RF/optical fading channels with CSI.

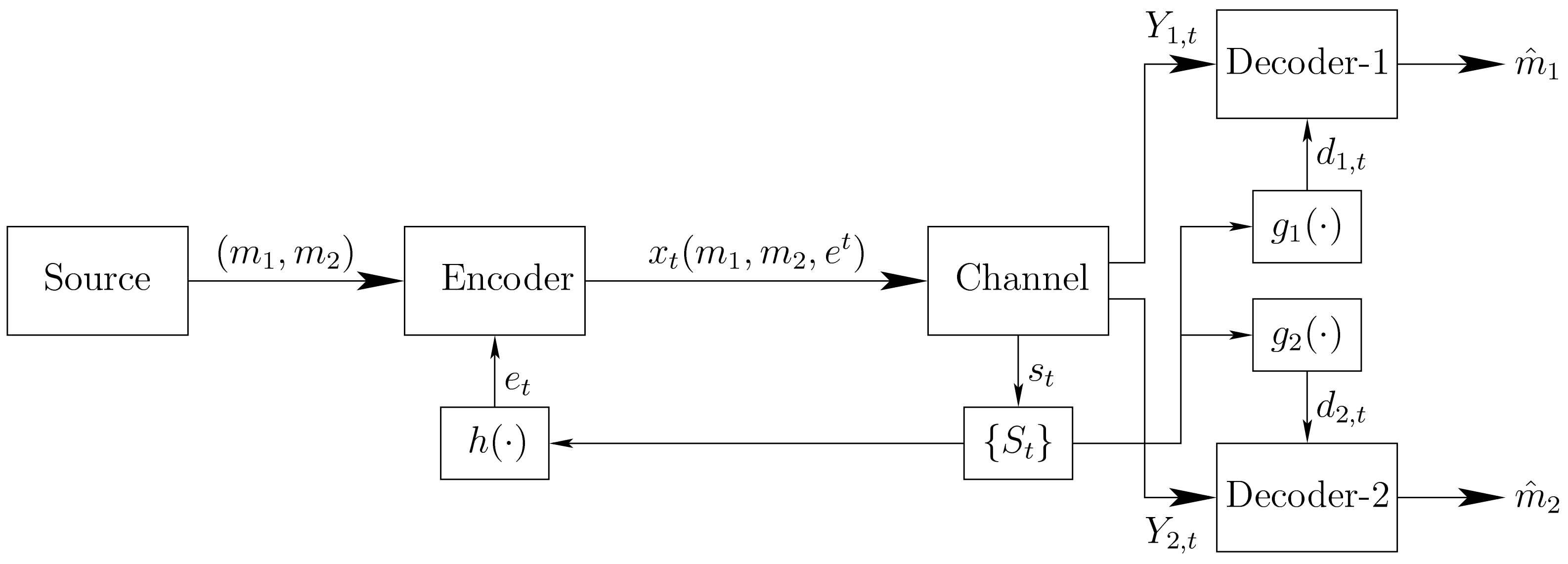
# Objectives

- To study how channel state information (CSI) can be gainfully used in devising transmitter and receiver strategies so as to enable reliable and efficient communication over time-varying RF channels.
- To understand how RF power control can be combined with RF/optical link-switching to achieve higher throughputs.
- To design optimal receiver structures for signal detection in the presence of optical link fading and thermal noise.

# **Time-Varying RF Broadcast Channel**

- Broadcast or “downlink” fading channel.
  - Information-theoretic capacity regions with CSI at the transmitter or receivers.
  - Effects of varying amounts of CSI on throughputs, and enhancements using schemes for
    - broadcast;
    - power control;
    - modulation and coding.

# Schematic for Time-Varying RF Broadcast Channel



- The state process $\{S_t\}$ evolves "autonomously," and current state $s_t$ may depend on previous states but not on previous channel inputs or outputs.

- $e_t = h(s_t)$, $d_{1,t} = g_1(s_t)$, $d_{2,t} = g_2(s_t)$ entail no loss in generality.

- CSI as noisy versions of $s_t$ can be incorporated into this model.

# References

- Shannon, ’58.
- Cover, ’72.
-
- Li, Goldsmith, ’01.
- Abou-Faycal, Trott, Shamai, ’01.
- Caire, Shamai, ’01, ’03.
- Yu, Cioffi, ’02.
- Vishwanath, Tse, ’02.
- Jindal, Viswanath, Goldsmith, ’02.
- Tuninetti, Shamai, ’03.
-
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# **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.
  - 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.
    - ?? (since no conditional Gaussianity).

# 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.

# Bounds on the Capacity Region

- Outer bound on capacity region obtained by providing CSI ordering at the transmitter and receivers, is in terms of power allocation policies:

$$P_k : \{0,1\} \rightarrow \mathbb{R}^+, \quad k = 1, 2,$$

satisfying

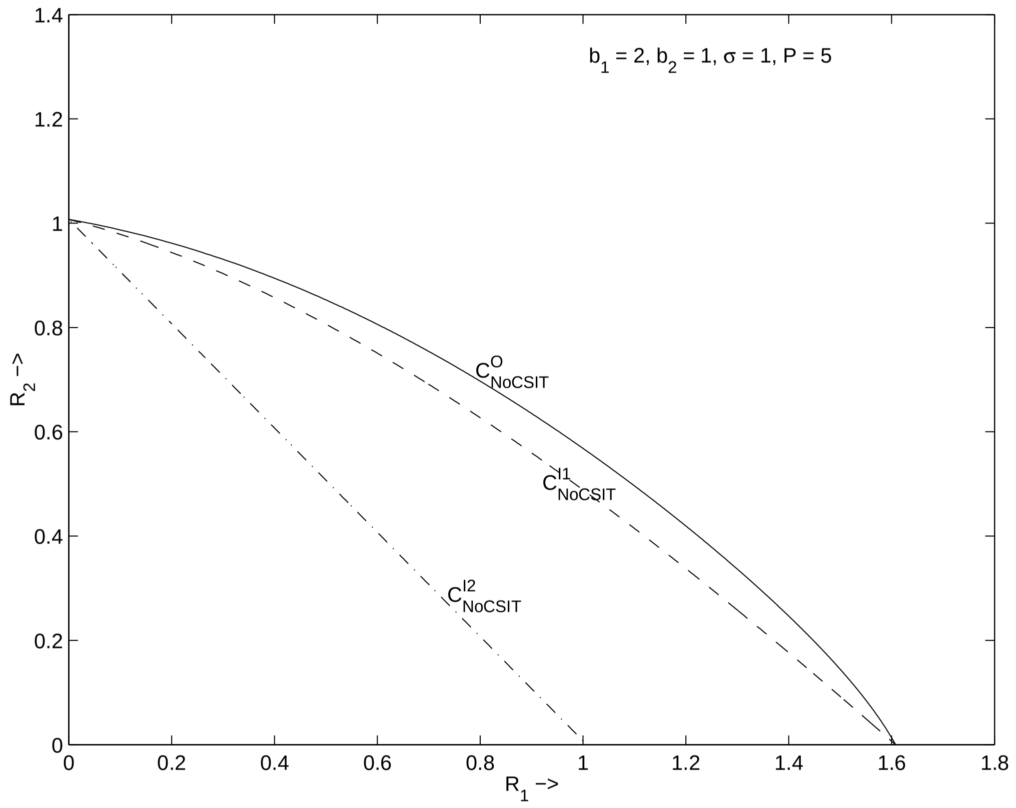
$$\mathbb{E}_S \left[ P_1(1(S_1 < S_2)) + P_2(1(S_1 < S_2)) \right] \leq P.$$

- Outer bound for capacity region: $C^O =$

$$\bigcup_{(P_1,P_2)\text{as above}} \left\{ \begin{array}{ccccc} 0 & \leq & R_1 & \leq & \mathbb{E}_S \left[ \frac{1}{2} \log \left( 1 + \frac{P_1(1(S_1<S_2))S_1^2}{P_2(1(S_1<S_2))S_1^2 1(S_1<S_2)+\sigma^2} \right) \right] \\ 0 & \leq & R_2 & \leq & \mathbb{E}_S \left[ \frac{1}{2} \log \left( 1 + \frac{P_2(1(S_1<S_2))S_1^2}{P_1(1(S_1<S_2))S_1^2 1(S_1\geq S_2)+\sigma^2} \right) \right] \end{array} \right\}.$$

- Inner bound for capacity region: $C^I = co(C_1^I \bigcup C_2^I)$, 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:

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

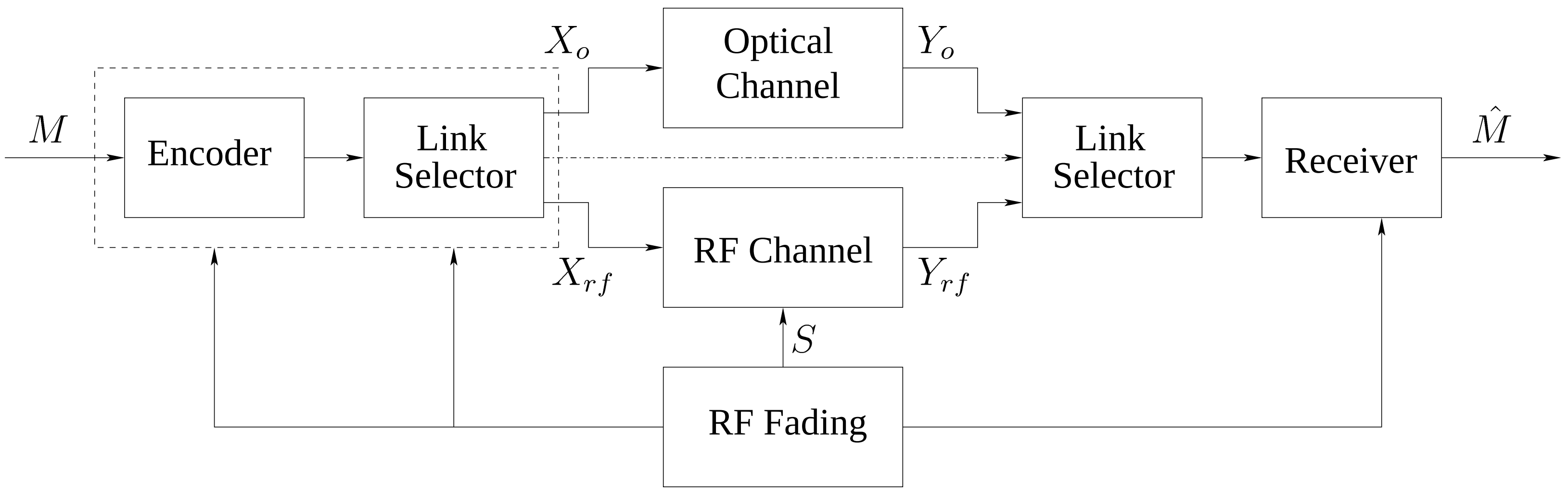
- Gap between inner and outer bounds:

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

# 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 ?

# 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.

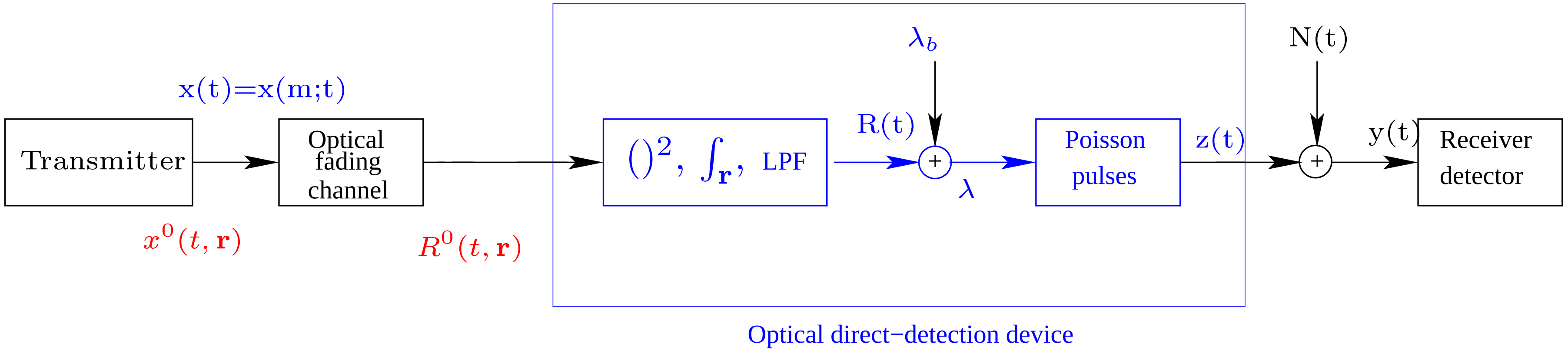
# Capacity Formula: Comments

- Determination of capacity formula
  - RF/optical “link-switching”
    - “Sum channel” with constraints: transmission of additional information.
    - Relationship to RF power control.

# Optical Fading Channel

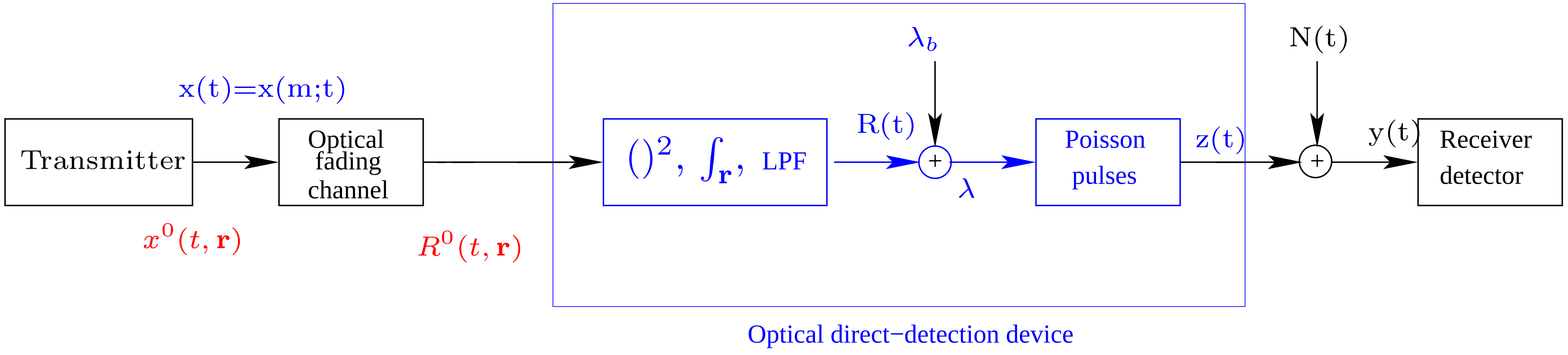
- Atmospheric turbulence, caused by differential thermal conditions in the troposphere, results in random variations in refractive index at optical wavelengths.
- A light beam propagating through the atmosphere suffers fading with random temporal and spatial fluctuations of amplitude and phase.
- This study addresses models for optical fading and associated receiver structures.

# Optical Fading Channel: Model, Receiver Structure



- Transmitted optical signal = $x^o(t,\mathbf{r}) = \sqrt{x(t)}\widetilde{x}(\mathbf{r})\cos(2\pi f_0 t), \quad 0 \le t \le T$.
- Optical channel output = $R^o(t,\mathbf{r}) = \widetilde{K}(t,\mathbf{r})x^o(t,\mathbf{r}) \simeq \widetilde{K}x^o(t,\mathbf{r})$, where $\widetilde{K}$ is a lognormal fade.
- $R(t) \simeq x(t)K$, where $K$ is lognormal.

# Optical Fading Channel: Model, Receiver Structure



- $\lambda(t) = R(t) + \lambda_d$, $\quad \lambda_d$ = dark current rate.
- $\{N(t), t \geq 0\}$ is white Gaussian noise with psd = $N_0/2$ watts/Hz.
- $\{Z(t), t \geq 0\}$ = process of Poisson "pulses" of rate $\lambda(t)$ where $Z(t) = \alpha \sum_{k=0}^{N(T)} g(t - T_k)$, with $g(\cdot)$ = a unit area pulse of duration $\ll T$.

# Relevant References

- Roggemann, Welsh, Fugate, ’97
- Zhu, Khan, ’00, ’01
-
- Davis, Smolyaninov, Milner, ’03
- Hass, Shapiro, ’03
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# Specific Problems

- Likelihood ratio formulae for on-off keying. ⇐
- Computational issues. ⇐
- Performance assessment.
- Optimal signaling.
- Capacity formulae.
  - CSI at the receiver.
- Combined use of RF/optical fading links.