Wireless Physical-layer Security: Outline

1. Wireless Modeling and Simulation
   - Modeling point-to-point wireless links
   - Modeling large wireless networks
   - Simulations do's and dont's
2. Information-theoretic security fundamentals
3. Case-study: Jamming for wireless secrecy
   - Effect of CSI on Jamming for Secrecy
   - Effect of Jammers' Location on Secrecy with Multiple Terminals
   - Jamming Protocol for Enhanced Wireless Secrecy

Wireless Physical-layer Security: Part I

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Wireless Physical-layer Security: Part II

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    - **d) Jamming Protocol for Enhanced Wireless Secrecy**

Wireless Modeling and Simulation:

Part I-a) Point-to-point Wireless Channel

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March 13, 2018

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2 Part II-a) Large Wireless Networks

3 Part II-b) Simulations Do's And Dont's

Wireless Channels

Affected by three main phenomena:

- Large-scale propagation effects:
  - Path loss: dissipation of power through space
  - Shadowing: attenuation of signal power due to objects
- Small-scale propagation effects:
  - Multipath fading: addition of multipath signal components

Wireless Channels

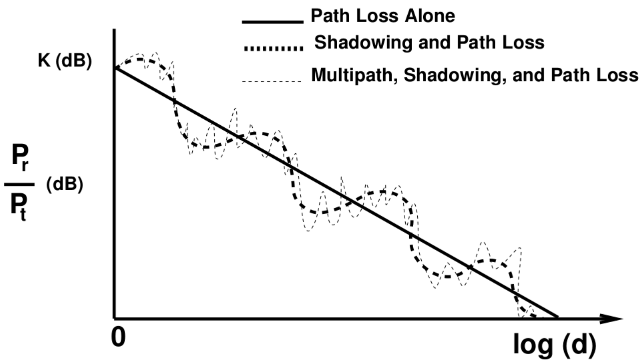
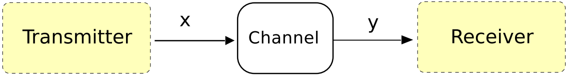


Figure: Path loss, multipath fading and shadowing vs distance

(source: Goldsmith's "Wireless Communications")

Channel Capacity

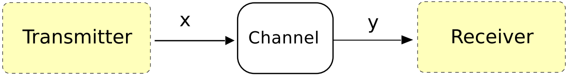
[Shannon, 1948]



- Maximum data rate that can be transmitted with asymptotically small error probability

Channel Capacity

[Shannon, 1948]



- Maximum data rate that can be transmitted with asymptotically small error probability
  - Mutual information between input $x \in \mathcal{X}$ and output $y \in \mathcal{Y}$

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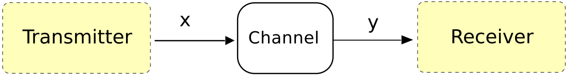
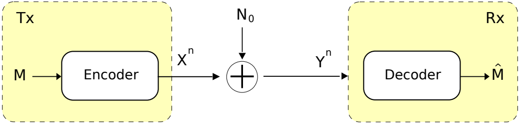


- Maximum data rate that can be transmitted with asymptotically small error probability
  - Mutual information between input $x \in \mathcal{X}$ and output $y \in \mathcal{Y}$
  - Maximized over all possible input distributions

$$C = \max_{p(x)} I(X;Y) = \max_{p(x)} \sum_{x,y} p(x,y) \log \left(\frac{p(x,y)}{p(x)p(y)} \right)$$

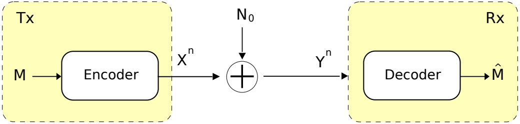
Additive White Gaussian Noise Channel



Impairment to communication comes from addition of white Gaussian noise. At time instant i:

$$\underbrace{y[i]}_{\text{output}} = \underbrace{x[i]}_{\text{input}} + \underbrace{n[i]}_{\text{noise}}$$

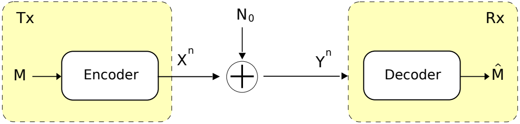
Additive White Gaussian Noise Channel (2)



Channel SNR: $\gamma = \dfrac{P_t}{N_0}$, where

- P_t: average transmit power
- N_0: power spectral density of noise

Additive White Gaussian Noise Channel (2)



Channel SNR: $\gamma = \dfrac{P_t}{N_0}$, where

- P_t: average transmit power
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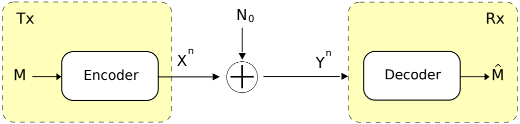
- Simple and tractable analytical model
- Good model for many satellite and deep space communication links

Capacity of Additive White Gaussian Noise Channel



$$C_{awgn} = \log_2(1+\gamma) = \log_2\left(1+\frac{P_t}{N_0}\right) \text{ bits/s/Hz}$$

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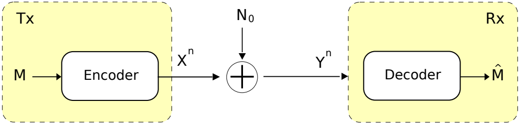

$$C_{awgn} = \log_2 (1 + \gamma) = \log_2 \left(1 + \frac{P_t}{N_0}\right) \text{ bits/s/Hz}$$

- Ultimate limit on the performance of such channels
- Building block to other more complex types of channels

Capacity with Path Loss

$$C = \log_2 \left(1 + \frac{P_t \cdot f(d_{tr})}{N_0} \right) \text{bits/s/Hz}$$

where d_{tr} is the distance between Tx and Rx.

---

d_0: reference close-in distance

α: path loss exponent

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Capacity with Path Loss

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Simplified path loss model: $f(d_{tr}) = (d_0/d_{tr})^\alpha$

- P_r is a function of distance: $P_r = P_t \cdot f(d_{tr})$ such that the path loss $PL = P_t/P_r$,

$$PL(d_{tr}) \propto \left(\frac{d_{tr}}{d_0}\right)^\alpha$$

or, in dB,

$$PL(d_{tr}) = PL(d_0) + 10\alpha \log_{10}\left(\frac{d_{tr}}{d_0}\right)$$

d_0: reference close-in distance
α: path loss exponent

Capacity with Shadowing

The previous simplified path loss model

$$PL(d_{tr}) = PL(d_0) + 10\alpha \log_{10}\left(\frac{d_{tr}}{d_0}\right)$$

assumes that PL is the same for every location with the same d_{tr}.

[1] e.g. blockage from objects, reflection over different surfaces

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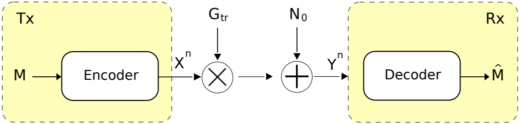
- This varies according to environmental-specific factors[1]
- Resort to statistical models, such as log-normal shadowing:

$$PL(d_{tr}) = PL(d_0) + 10\alpha \log_{10}\left(\frac{d_{tr}}{d_0}\right) + X_\sigma,$$

where X_σ is a Gaussian distributed random variable with mean zero and variance σ.

[1] e.g. blockage from objects, reflection over different surfaces

Capacity with Fading



$$C = \log_2 \left(1 + \frac{P_t \cdot G_{tr}}{N_0} \right) \text{ bits/s/Hz}$$

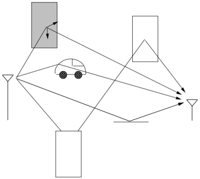
- G_{tr}: stochastic fading process between Tx and Rx

Capacity with Fading (2)

$$C = \log_2 \left(1 + \frac{P_t \cdot G_{tr}}{N_0} \right) \text{bits/s/Hz}$$

Two common statistical multipath fading models:

- **Rayleigh fading**: environment with multiple independent scattered paths between transmitted and receiver
- **Rician fading**: predominant propagation along a line of sight between transmitter and receiver



- Many others exist [4]

Types of Fading

Coherence time: time scale at which fading varies wrt the symbol rate

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Coherence time: time scale at which fading varies wrt the symbol rate

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- Fast fading: coherence time is small and the transmission of a symbol may experience several fading realizations.

- Different notions of capacity according to the type of fading considered

Capacity of Slow Fading Channels

Outage probability of capacity when the transmitter sends data at a communication rate of R bits/s/Hz:

$$\mathcal{P}_{out}(R) = \mathbb{P}\{C < R\} = \mathbb{P}\left\{\log_2\left(1 + \frac{P_t \cdot G_{tr}}{N_0}\right) < R\right\}$$

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- Maximum rate that can be achieved with some outage probability
- Outage means not being able to decode the transmission with arbitrarily low probability of error

Average rate correctly received: $R(1 - \mathcal{P}_{out}(R))$.

Capacity of Fast Fading Channels

Ergodic capacity:

$$C = \mathbb{E}\left\{\log_2\left(1 + \frac{P_t \cdot G_{tr}}{N_0}\right)\right\} \text{bits/s/Hz}$$

- Each symbol may experience many fading realizations
- Capacity can be analyzed by averaging over many independent fades

Capacity of Fast Fading Channels

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- Each symbol may experience many fading realizations
- Capacity can be analyzed by averaging over many independent fades
- Rate of communication can be achieved reliably by coding over a large number of coherence time intervals

Channel State Information (CSI)

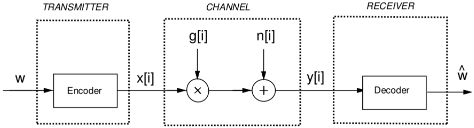

Figure: source: Goldsmith's "Wireless Communications"

- CSI: the channel fading gains (g)
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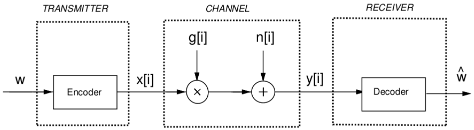

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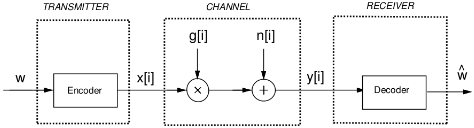

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- CSI: the channel fading gains (g)
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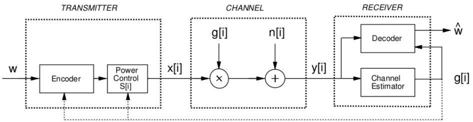
- The SNR $\gamma = \frac{P_t \cdot G_{tr}}{N_0}$ varies with time: $\gamma[i] = \frac{P_t \cdot g[i]}{N_0}$
- Previous definitions of capacity (outage and ergodic):
  - Implicitly assume CSI at Rx only
  - Tx chooses a constant transmission rate R:
    - Reliable communication is possible when $R < \mathrm{C}$

Channel State Information (2)



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CSI available at Tx:

- No notion of outage probability of capacity
- Transmission rate no longer constant
- Optimal power and rate adaptation

Channel State Information (3)

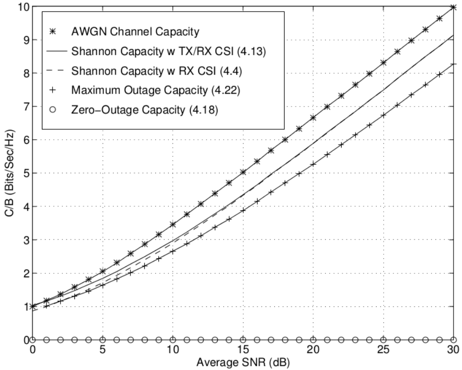

Figure: Capacity vs SNR in Rayleigh Fading

(source: Goldsmith's "Wireless Communications")

Channel State Information (3)

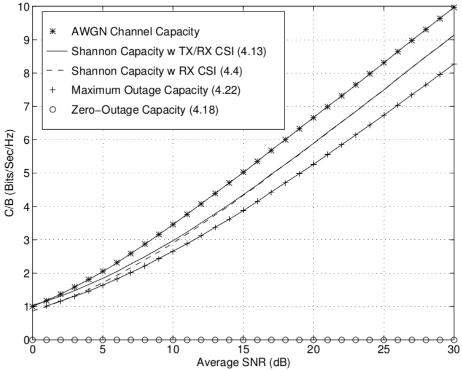

Figure: Capacity vs SNR in Rayleigh Fading

(source: Goldsmith's "Wireless Communications")

- AWGN capacity is always higher
- TX/RX CSI approaches AWGN at low SNR

Capacity with Multiple Users and Interference

From SNR to SINR (signal-to-interference-plus-noise ratio):

$$C = \log_2(1 + \mathrm{SINR}) = \log_2\left(1 + \frac{P_t}{N_0 + I}\right)^{\dagger}$$

- I captures the effect of interference from the remaining transmitting devices:

$$I = \sum_i \frac{P_i \cdot G_{ir}}{d_{ir}^{\alpha}},$$

where

- P_i: average power constraint of the i-th interferer
- G_{ir}: fading gain between interferer i and the receiver
- d_{ir}: interferer-receiver distance

† only a good approximation if interference has approx. Gaussian statistics (e.g. large number of interferers).

Summing Up...

- So far – Performance limits of a point-to-point link
  - Path loss
  - Fading
  - Shadowing
  - Channel state information
  - Multiple users and interference

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- Next: Part I-b) Information-theoretic security

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Modeling the Spatial Location of Devices

- Typical deterministic models (structured distribution):
  - grid networks
  - line networks
  - triangular lattices

Modeling the Spatial Location of Devices

- Typical deterministic models (structured distribution):
  - grid networks
  - line networks
  - triangular lattices
- Uncertainty about location – stochastic geometry:
  - average behavior over many spatial realizations
  - nodes placed according to some probability distribution

Point Processes

Point process (PP): random set of points $\{x_1, x_2, \ldots, x_n\}$ in a plane.

- Total number of points of a PP falling in a given region of space is a random variable
- Number of points within a certain region of $\mathbb{R}^2$ can be analyzed probabilistically

Poisson Point Process

- Simplest and most important class of spatial processes
  - Homogeneous PPP: regular distribution of points
  - Inhomogeneous PPP: irregular deployments

$\mathbb{A}\{\mathcal{R}\}$ - area of region $\mathcal{R}$

Poisson Point Process

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  - Homogeneous PPP: regular distribution of points
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Homogeneous PPP:

- characterized by a density parameter λ
- expected number of points in a region $\mathcal{R}$ follows a Poisson distribution with parameter $\lambda \cdot \mathbb{A}\{\mathcal{R}\}$
- probability of n nodes being inside a region $\mathcal{R}$ is:

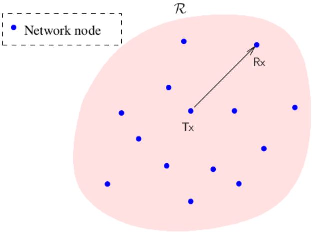
$$\mathbb{P}\{n \text{ nodes in } \mathcal{R}\} = \frac{(\lambda \cdot \mathbb{A}\{\mathcal{R}\})^n}{n!} e^{-\lambda \cdot \mathbb{A}\{\mathcal{R}\}}.$$

$\mathbb{A}\{\mathcal{R}\}$ - area of region $\mathcal{R}$

Homogeneous Poisson Point Process

Realization in a region $\mathcal{R}$:

1) draw a random number N of points from a Poisson distribution with parameter $\lambda \cdot \mathbb{A}\{\mathcal{R}\}$
2) scatter those N points uniformly at random inside $\mathcal{R}$

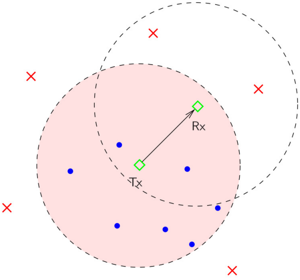


- These points can represent locations of devices of a wireless network

Random Networks

– Networks formed by connections between nodes of a Point Process in space
– Connectivity among nodes according to several types of bonds:

1) Boolean model: two nodes connected if some condition (e.g. minimum received signal strength) is satisfied
2) Collision model: a node is audible to another if the received power is above a certain threshold



Random Networks: Boolean Model

- Two nodes at locations x_i, x_j are connected if some condition is satisfied
- Condition can be a required minimum received signal strength θ when nodes transmit with power P_t
- Connectivity given by the following set of links:

$$\mathcal{L} = \left\{ \overline{x_i x_j} : \frac{P_t \cdot f(d_{ij})}{N_0} > \theta \right\}$$

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- Fixing θ is equivalent to setting a communication radius r s.t. two nodes are connected if their distance is below r
- Model can be extended to include fading and shadowing

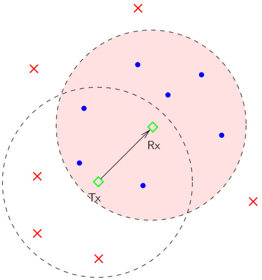
Random Networks: Collision Model

Based on the concept of audible node

- A node x is audible to y if the received power from x at y is above a certain predefined threshold P^*
- Number of audible nodes N_A for nodes distributed according to a homogeneous PPP with density λ:

$$N_A \sim \mathcal{P}(\mu_A), \text{ with } \mu_A = \lambda\pi \left(\frac{P_t}{P^*}\right)^{1/b}$$

- Model can be extended to include fading and shadowing



Random Networks: Collision Model (2) [Pinto & Win, Milcom 2008]

- A node Rx receives a packet from Tx with success if packets from other audible nodes do not collide with the desired packet from Tx
- The packet throughput of a *typical link*[4] relates to the probability that no collision happens

$$
\begin{aligned}
\mathbb{P}\{\text{no collision}\} &= \sum_{n=0}^{\infty} \mathbb{P}\{\text{no collision} | N_A = n\} \mathbb{P}\{N_A = n\} \\
&\overset{(*)}{=} \sum_{n=0}^{\infty} p_S^n \frac{\mu_A^n e^{-\mu_A}}{n!} \\
&= e^{-\mu_A} e^{\mu_A p_S} \underbrace{\sum_{n=0}^{\infty} \frac{(\mu_A p_S)^n e^{-\mu_A p_S}}{n!}}_{=1} \\
&= \exp(-\mu_A(1 - p_S)).
\end{aligned}
$$

[4] characterizes the average link performance in the network

Capacity of Wireless Networks [Gupta & Kumar, 2000]

Assumptions:

- All n nodes required to transmit at the same bit-rate
- Power law of distance: $f(d_{tr}) = d_{tr}^{-\alpha}$
- Collective interference approximated as Gaussian noise
- Multi-hop operation, pairwise coding and decoding per hop
- Rate of any point-to-point link: $\log_2\left(1 + \frac{P_t d_{tr}^{-\alpha}}{N_0 + \mathrm{I}}\right)$

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Main result:

- Square-root law: bit-rate$_{n\to\infty}$ decreases as $\frac{1}{\sqrt{n}}$

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Main result:

- Square-root law: bit-rate$_{n\to\infty}$ decreases as $\frac{1}{\sqrt{n}}$

- Less disappointing results with:
  - cooperation among nodes
  - interference cancellation
  - fading

"The value of a solution is largely determined by the model and assumptions used to derive it"

Is the PHY Layer Dead?, IEEE Comms Magazine, April 2011

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Simulation?

- It is (generally) easier to verify the correctness of a mathematical model than of an extensive and complex software
- The simulation software is usually a simplification of a real-world system
- Statistical uncertainty in results
- Overhead of debugging simulations is (usually) high

Simulation!

- Analytically intractable systems
- Real-world: expensive or limited scale
- Complementary to the analytical model
- Useful to examine particular aspects
- Yields estimates of measures of system performance
- Helps researchers develop intuition

Wireless Simulation

- Can be performed using several tools (network simulator, opnet, matlab, matplotlib, ...)

- Network simulator 3:
  - Implements all layers of the communication stack
  - Including, for example, the 802.11b physical layer model, that incorporates the simple log-distance path loss model:

$$PL(dB) = PL(d_0) + 10\alpha \log_{10}\left(\frac{d}{d_0}\right)$$

  - Also includes models such as multipath Rayleigh fading and log-normal shadow fading

Wireless Simulation: Common Pitfalls

[Kurkowski et. al, 2005]

- Lack of provided information:
  - No identification of simulator versions
  - Unavailability of code and configuration files
  - Omission of legends or labels on charts
  - Unexplained/unsupportive charts
- No verification of the correctness of software implementation
- Initialization bias not taken into account
- No PRNG verification and validation
- Lack of consistent rigorous scenarios
- Use of incorrect statistical analysis

Wireless Simulation: Initialization Bias

Early stages of simulation affected by aspects such as

- Empty queues
- Speed decay in random mobility models

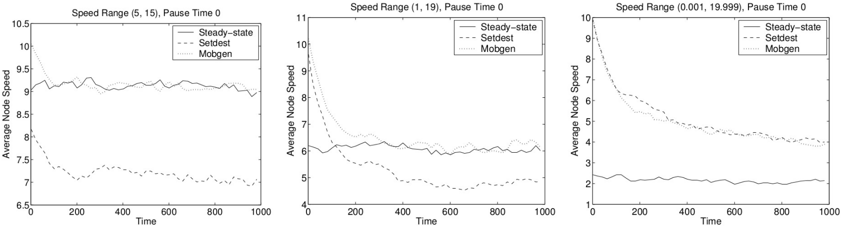

Figure: Average speed as a function of time for mobility models

(source: Navidi,Camp,Bauer, “Improving the Accuracy of Random Waypoint Simulations Through Steady-State Initialization”)

Wireless Simulation: Initialization Bias – Solutions

- Discard first seconds of simulation
  - Not reliable
  - Difficult to determine proper value

- Determine steady-state/stationary distribution
  - Initial values chosen from already stationary distribution
  - No longer suffer from initialization bias

  - Perfect simulation and stationarity of a class of mobility models, Infocom 2005 Best Paper
    - Tool to generate mobility traces: http://icawww1.epfl.ch/RandomTrip/

Wireless Simulation: Statistical Analysis [Goldsman & Tokol, 2000]

- Simulations almost never produce output that is i.i.d.
- Classical statistical techniques cannot be applied directly

- Method of independent replications:
  1. Conduct b independent simulation runs/replications
  2. Each replication i consists of m observations, $Y_{i,1}, \dots, Y_{i,m}$
  3. The sample mean from replication i is $Z_i = \frac{1}{m}\sum_{j=1}^{m} Y_{i,j}$
  4. If the number of observations per replication m is large enough, a CLT tells us that the replicate sample means are approximately i.i.d. normal, and the approximate $100(1-\alpha)\%$ two-sided confidence interval for all observations is

$$\overline{Z}_b \pm t_{\alpha/2,b-1}\sqrt{\hat{V}_R/b},$$

where $\hat{V}_R = \frac{1}{b-1}\sum_{i=1}^{b}(Z_i - \overline{Z}_b)^2$, and $\overline{Z}_b = \frac{1}{b}\sum_{i=1}^{b} Z_i$

$t_{\alpha/2,b-1}$: $1-\alpha/2$ quantile of the t-distribution with $b-1$ degrees of freedom

Summing Up

- Capacities of single-link channels
  - Pathloss, shadowing, fading
  - Channel state information
  - Multiple users and interference
- Stochastic geometry for analysis of large networks
- Simulation (pitfalls)

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Next:

- Part II-c) Effect of Jammers' Location on Secrecy with Multiple Terminals
- Part II-d) Jamming Protocol for Enhanced Wireless Secrecy

Main References

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