

# Cellular System Performance Analysis Under Correlated Shadow Fading

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# Overview

- 1 Motivation
  - Why Correlated Shadow Fading
- 2 Cooperative Communication for a Single-Cell Model
  - Angular and Distance Correlation Model
  - How Cooperative Communication Mitigate Shadow Fading
- 3 Single-Cell System Performance Analysis
  - First-Order Markov Chain Model
  - Analysis of Outage Behavior
- 4 Multi-Cell System Performance Analysis
  - Grid Model vs. Random Model
  - Outage Probability and Outage Durations
- 5 Transport Layer Protocols for Next Generation Networks
  - Motivation
  - Data-Driven End-User Congestion Prediction Algorithm
- 6 Conclusions and Future Work

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# Introduction of Fading

In general, fading can be divided into two categories: large-scale fading and small-scale fading

- Large-scale fading: shadow fading caused by obstacles (trees, buildings, etc.) in the propagation path.
- Small-scale fading: caused by multipath propagation.

Next Generation Cellular Networks:

- Millimeter wave (mmWave) frequency spectrum, between 30 and 300 GHz, will most likely be used to address the bandwidth needs.
- The small wavelengths of mmWave will result in high path loss and sensitivity to obstructions which cause large-scale shadow fading.
- Shadow fading can lead to significant received power loss over a wide area.

# Correlated Shadow Fading

In general, shadow fading is approximated by an independent log-normal distribution with a standard deviation derived from empirical measurements.

This model fails to capture the spatial correlations in shadow fading.

A mobile user moving  
behind a row of tall  
buildings.

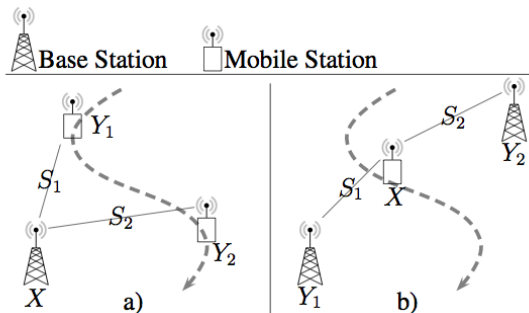


# Shadow Fading Correlation Models

## Specific Correlation Models:

- Constant Model
- Absolute Distance-Only Models: Exponential Model
- Angle-Only Models
- Separable Models: Angle-Distance Ratio and Angle-Absolute Distance

## Autocorrelation and Cross-Correlation:



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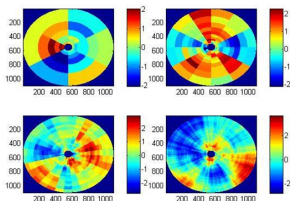
# Angular and Distance Correlation Model

We consider a correlation model involves both angular and distance as follows:

$$\theta = |\angle \vec{r}_i - \angle \vec{r}_j| \in [0^\circ, 180^\circ], \quad (1)$$

$$R = |10 \log_{10} r_i / r_j| = \frac{10}{\ln 10} |\ln r_i - \ln r_j|, \quad (2)$$

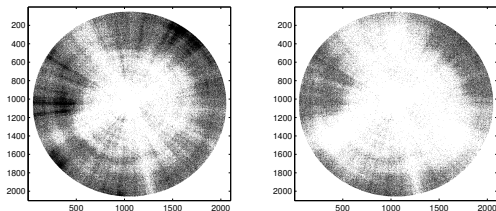
$$h(\vec{r}_i, \vec{r}_j) = \max\{1 - \theta/\theta_0, 0\} \cdot \max\{1 - R/R_0, 0\}. \quad (3)$$



Correlated Shadowing Fields for Increasing Resolutions



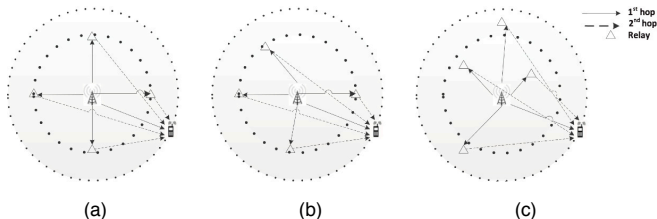
# Correlated Outage Fields



Correlated Outage Fields (Dark areas are outage areas while white areas are non-outage areas)

# System Model

A single cell cellular deployment.



System Model and Three Different Relay Placements

- Relays are placed uniformly on a circle near the cell edge.
- Relays are randomly spaced on a circle near the cell edge.
- Relays are placed randomly in the cell.

# Cooperative Communication Scheme

- First Hop: BS broadcasts signals to both relays and MS. If MS receives and decodes the signals transmitted by BS successfully, there is no need for relays to repeat the transmission. If not, relays which successfully decode the signals will participate in the second hop retransmission. Relays which cannot decode the received signal successfully, will not participate in the second hop.
- Second Hop: Among all relays which participate in the second hop, the one that has the best channel gain between the relay and MS will be chosen (this can be done by centralized control or using information from pilot signals). This relay will encode the signals again and send the coded bits to the MS.

# Outage Probability of the System

The outage probability of the system:

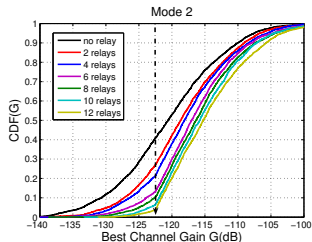
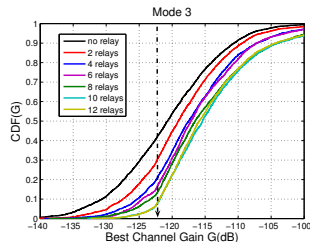
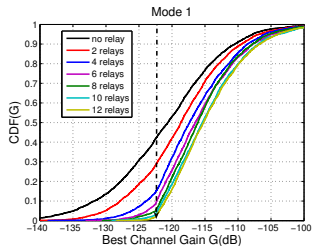
$$P_{out_S} = P_{out_0} * (P_{out_1} + (1 - P_{out_1}) * P_{out_2}). \quad (4)$$

# Simulation and Performance Evaluation

## Simulation Configuration Parameters

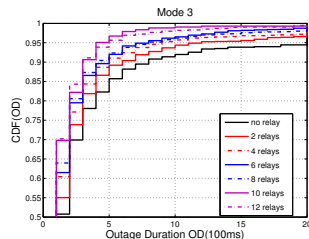
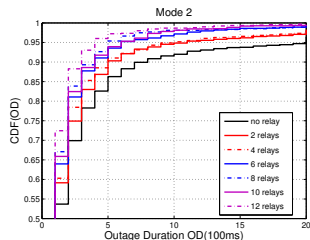
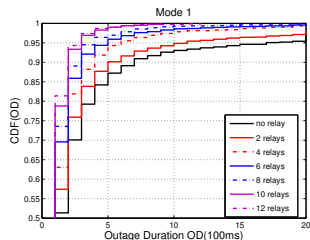
Okuruma-Hata Model	BS Height: 100m Relay Height: 10m MS Height: 1.5m
Correlated Shadow Fading	$R_0 : 6$ $\theta_0 : \pi/3$ $d_{min} : 50m$
Relay Placements	Three Modes with Density: 2,4,6,8,10,12
Cell Size	$R : 1000m$
MS Moving Speed	$v : 10m/s$
Radio Frequency	$f : 900MHz$
BS Transmission Power	$P : 26dbm$
SNR Requirement	8dB

# Simulation Results and Analysis



Best Channel Condition between MS and BS or Relays (corresponding to three different relay deployment modes and several different relay densities. Dashed arrow demonstrates the channel condition that satisfies the SNR requirement.

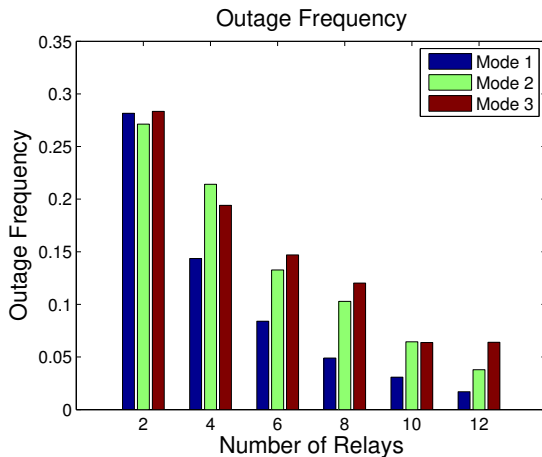
# Outage Duration



Cumulative Distribution Function of Outage Duration (with Rayleigh fading)

# Outage Frequency

$$f_{outage} = \frac{\text{Total Number of Outage Points}}{\text{Total Number of Simulation Points}}. \quad (5)$$





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# Exponential Correlation Model

Exponential correlation model is an analytical model proposed by Gudmundson based on empirical measurements of 900MHz frequency.

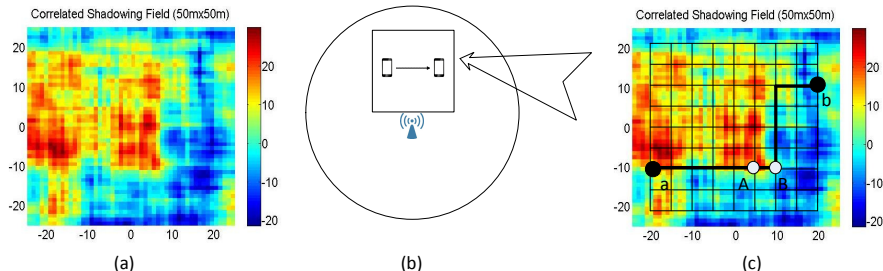
$$\rho = e^{-\frac{d}{d_0}} \quad (6)$$

- Derived from empirical measurements.
- Does not violated physical rules.
- Correlation matrix is positive semi-definite.
- Can be modeled as a first-order autoregressive process spatially.
- Has low simulation complexity.

## Disadvantage

The correlation is only decided by  $d$ ,  $\theta$  is ignored.

# Exponential Correlated Shadowing Field



(a) A typical exponential correlated shadow fading field in a  $50m \times 50m$  area. The color bar denotes the value of the shadow fading in dB. (b) A single cell model with a MS moving on a fixed trajectory. The shadow fading field covered the entire trajectory is generated locally. (c) A locally generated correlated shadowing field for a fixed trajectory from point a to point b.

# Exponential Correlation

$A$  and  $B$  are two neighboring points. Assume the shadow fading (in dB) is  $N(0, \sigma^2)$ .

The spatial correlation between  $S_A$  and  $S_B$  is:

$$\rho_{A,B} = \frac{E[S_A S_B]}{\sigma^2} = e^{-\frac{d_{A,B}}{d_0}} \quad (7)$$

This can be written as:

$$S_B = \rho S_A + (1 - \rho) n_A \quad (8)$$

where  $n_A$  denotes the channel noise at  $A$ .

# Construct Markov Chain Model

## Lemma

*Shadow fading factors of any two points that can be connected by a trajectory have jointly gaussian distribution.*

- Divide the entire shadow fading range  $[-\infty, +\infty]$  into finite number of intervals  $\{[-\infty, S_0], [S_0, S_1], \dots, [S_N, +\infty]\}$ . Each interval represents a state of the Markov chain model.
- Derive the state transition matrix of the Markov chain model from the probability distribution of the correlated shadow fading.
- Derive the steady-state probability from the state transition matrix of the Markov chain model.

# State Transition Matrix

Assume there are  $N$  states of the Markov chain model  $ST_1, ST_2, \dots, ST_N$  where  $ST_i$  corresponds to interval  $(S_{i-1}, S_i]$ . Then we have the state transition probability as follows:

$$\begin{aligned} P_{i,j} &= P(S_A \in ST_j | S_B \in ST_i) \\ &= \frac{P(S_A \in ST_j, S_B \in ST_i)}{P(S_B \in ST_i)} \\ &= \frac{\int_{S_{i-1}}^{S_i} (\int_{S_{j-1}}^{S_j} f_{(S_A|S_B=s_B)}(s_A) ds_A) f(s_B) ds_B}{\int_{S_{i-1}}^{S_i} f(s_B) ds_B} \end{aligned} \tag{9}$$

Considering two consecutive points  $A$  and  $B$ , we have  $G_A = PL_A(d_A) + S_A$  and  $G_B = PL_B(d_B) + S_B$ . The probability of  $A$  and  $B$  are both in outage area can be written as:

$$\begin{aligned} P(G_A < \gamma, G_B < \gamma) \\ = P(S_A < \gamma - PL_A(d_A), S_B < \gamma - PL_B(d_B)) \end{aligned} \quad (10)$$

If  $S_A < \gamma - PL_A(d_A) \in ST_i$  and  $S_B < \gamma - PL_B(d_B) \in ST_j$ , we can infer that, to avoid outage, the lower bound of shadow fading factor  $S_A$  is in state  $ST_i$  and for  $S_B$  is in state  $ST_j$ . State  $ST_i$  and  $ST_j$  are called lower bound state.

# Outage Behavior Cont'd

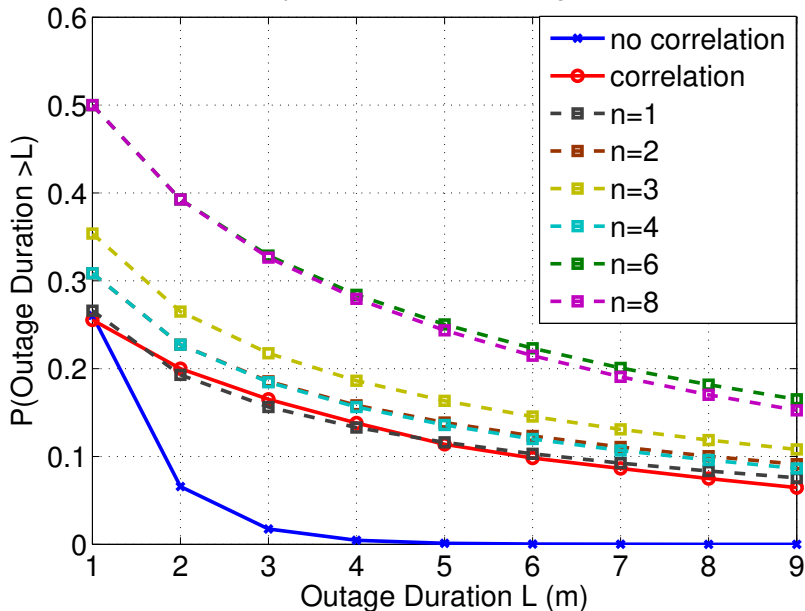
$$P(G_A < \gamma, G_B < \gamma) = \sum_{m=0}^i \sum_{n=0}^j P(ST_m) \bullet P(ST_m, ST_n) \quad (11)$$

$$\begin{aligned} P(G_1 < \gamma, \dots, G_L < \gamma) = \\ \sum_{m_1=0}^{M_1} \cdots \sum_{m_L=0}^{M_L} P(ST_{m_1}) \bullet P(ST_{m_1}, ST_{m_2}) \\ \bullet \cdots \bullet P(ST_{m_{L-1}}, ST_{m_L}) \end{aligned} \quad (12)$$

where  $m_i, i \in \{1, \dots, L\}$  are corresponding lower bound state of each position on the moving trajectory.



# Probability Distribution of Outage Duration L

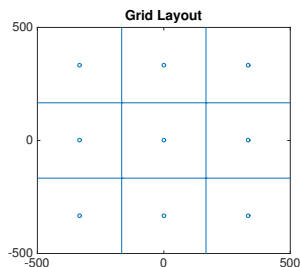
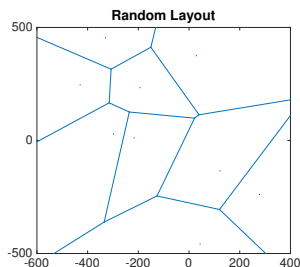


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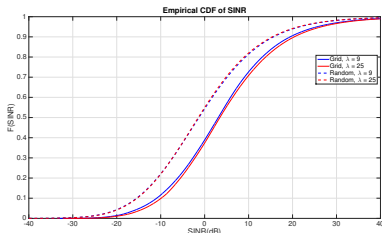
# Multi-Cell System Model

- Grid Model:  $\lambda$  BSs are placed on a regular grid deterministically.
- Random Model:  $\lambda$  BSs are placed randomly in a fixed area.

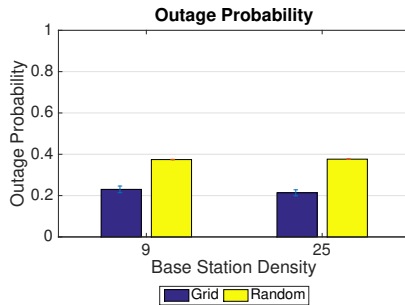


Random model and Grid model with  $\lambda = 9$ .

# Grid Model vs. Random Model



CDF of SINR given Grid model and Random model (de-correlation distance: 20m)



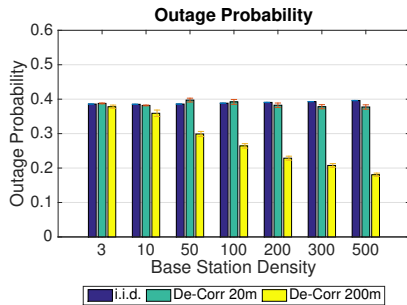
Outage probability given Grid model and Random model with  $\gamma = -5dB$  (de-correlation distance: 20m)

# Outage Probability Simulation

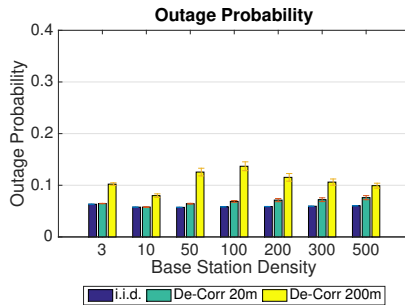
Simulation Configuration Parameters

Target Area	$1000m \times 1000m$
BS Densities	3, 10, 50, 100, 200, 300, 500
Path Loss Exponent	4
BS Transmission Power	$P : 40dbm$
SINR Requirement	$-5dB$
De-Correlation Distance	20m, 200m

# Outage Probability Analysis

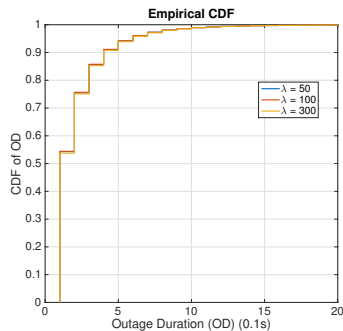


Outage probability given  $-5dB$  SINR threshold (MS connecting to the Nearest BS)

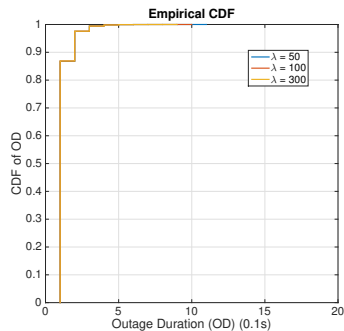


Outage probability given  $-5dB$  SINR threshold (MS connecting to the Strongest BS)

# Outage Duration Analysis

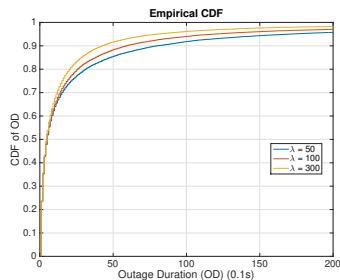


CDF of Outage Durations when the MS is connecting to the Nearest BS with independent shadow fading

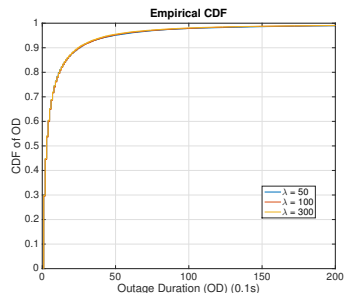


CDF of Outage Durations when the MS is connecting to the Strongest BS with independent shadow fading

# Outage Duration Analysis Cont'd



CDF of Outage Durations when MS is connecting to the Nearest BS with correlated shadowing (de-correlation distance: 200m)



CDF of Outage Durations when MS is connecting to the Strongest BS with correlated shadowing (de-correlation distance: 200m)



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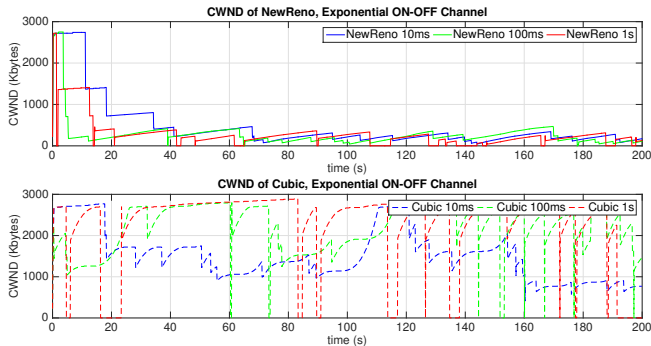
## MmWave Channel:

- High capacity and low delay.
- Sensitive to obstructions, which result in frequent capacity fluctuations.
- Switch between line-of-sight (LOS) state and none-line-of-sight (NLOS) state periodically.

## Legacy TCP

Legacy TCP congestion control protocols might not work well with mmWave channel due to the slow congestion detection and conservative loss recovery.

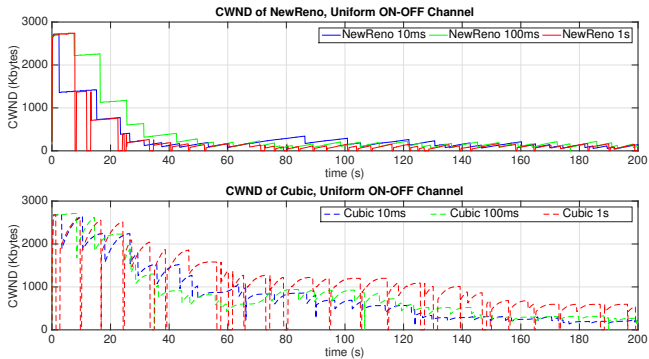
# Test Legacy TCP on an Emulated MmWave Channel



CWND dynamics given exponentially On-Off channel behavior

# Test Legacy TCP on an Emulated MmWave Channel

## Cont'd



CWND dynamics given uniformly On-Off channel behavior

Remy is a congestion-control scheme based on prior knowledge of the network and the traffic model. It is the first computer generated congestion control protocol. A RemyCC tracks only three state variables of the end-user:

- An exponentially weighted moving average (EWMA) of the inter-arrival time between new ACKs received (`ack_ewma`).
- An EWMA of the time between TCP sender timestamps reflected in those ACKs (`send_ewma`).
- The ratio between the most recent Round Trip Time (RTT) and the minimum RTT during the current connection (`rtt_ratio`).

This algorithm does not require the support from any intermediate network devices. The end-user can adjust its sending speed following the pre-generated algorithm based on the above data.

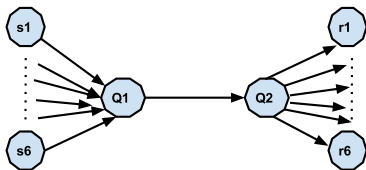
# Explicit Congestion Notification (ECN)

With the addition of active queue management and ECN to the network infrastructure, routers are capable of detecting congestion before queue overflows.

- An additional Congestion Experienced (CE) byte is added to the IP header of the packet to support this function.
- Routers running RED queue management can mark the CE code point with a certain probability when the average queue length satisfies a certain criteria.
- The packet with marked CE will be sent to the receiver.
- After receiving the packet, the receiver will piggyback an ACK with marked CE to notify the sender that congestion occurs in the router.

No extra traffic will be generated to overload the network. The sender will reduce the congestion window to avoid queue overflow and packet loss. Using ECN to detect congestion requires the participation of routers and receiver's feedback.

# End-user Data Collection



Network topology

- 6 traffic senders and 6 receivers.
- The sender  $s_i$  sends data to receiver  $r_i$  through the bottleneck link  $Q1 \rightarrow Q2$ .
- Both Q1 and Q2 maintain DropTail Queues.
- The queue limit is set to be the bandwidth-delay product to ensure the full utilization of the link capacity.

# End-user Data Collection Cont'd

Without losing of generality, we simulated several different traffic scenarios to collect end-user data. We analyze the following scenarios:

- Scenario 1: All traffic sources are running TCP NewReno with stationary bottleneck link capacity.
- Scenario 2: All traffic sources are running TCP Cubic with stationary bottleneck link capacity.
- Scenario 3: One-half of the traffic sources is running TCP NewReno while the other half is running UDP with stationary bottleneck link capacity.
- Scenario 4: One-half of the traffic sources is running TCP Cubic while the other half is running UDP with stationary bottleneck link capacity.
- Scenario 5: Repeat scenario 1 and 2 for a periodically On-Off bottleneck link.

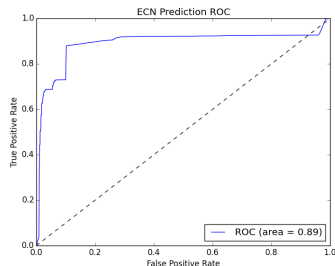


Simulation Parameters

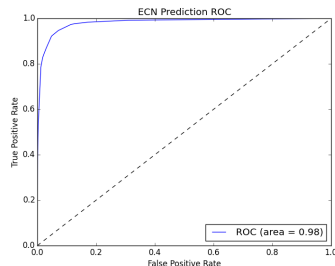
Access Link Capacity	1Gbps
BottleNeck Link Capacity	1Gbps
Access Link Delay	5ms
BottleNeck Link Delay	10ms
Queue Capacity	Bandwidth-Delay Product

- The sending time interval between two consecutive packets  $T_{s_i}$ .
- The receiving time interval between two consecutive ACKs  $T_{r_i}$ .
- An EWMA of  $T_{s_i}$  (send\_ewma).
- An EWMA of  $T_{r_i}$  (ack\_ewma).
- The ratio between the most recent RTT and the minimum RTT during the entire connection period (rtt\_ratio).

# Receiver Operating Characteristic (ROC) Curves



ROC curve of the Logistic Regression classifier



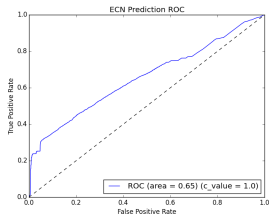
ROC curve of the Decision Tree classifier  
(max\_depth = 5, min\_samples\_leaf = 10000)

- Logistic Regression: the decision boundary is  
$$-2.32 * f_1 - 33.36 * f_2 - 12.65 * f_3 - 15.30 * f_4 + 2.03 * f_5 - 2.69 = 0.$$
- Decision Tree: the feature importance is given as [0.011703, 0.00085, 0.000000, 0.03985, 0.94760].

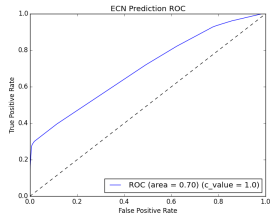
# Receiver Operating Characteristic (ROC) Curves

## Simulation Parameters

Access Link Delay	5ms, 10ms, 20ms
BottleNeck Link Delay	10ms, 20ms, 40ms
Queue Capacity	Bandwidth-Delay Product



ROC curve of Logistic Regression classifier with different propagation delays



ROC curve of Decision Tree classifier with different propagation delays

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## Conclusions:

- Cooperative communication can be used to mitigate correlated shadow fading, reduce outage frequency and probability of long-lasting outage durations.
- A first-order Markov Chain Model can be constructed to analyze the system performance under exponential correlated shadow fading.
- The performance of a multi-cell system is investigated from the outage probability and outage durations. Connecting to the BS providing highest SINR or increasing the BS density can improve the system performance.
- A data-driven end-user congestion detection algorithm is developed for stable networks.

## Future Work:

- Apply our algorithms to mitigate correlated shadow fading to the standard mmWave channel.
- Use the proposed fast end-user congestion prediction algorithm to design fast reacting TCP congestion control algorithms for stable networks.
- Extract new features and apply powerful machine learning algorithms to design fast reacting TCP congestion control algorithms for unstable networks.

## Publications:

- "Shining a Light into the Darkness: How Cooperative Relay Communication Mitigates Correlated Shadow Fading", Accepted by VTC 2015 Spring.
- "How Long Before I Regain My Signal?", Accepted by CISS 2015.

## Technical Report:

- "Virtual ECN: A Data-Driven End-User Congestion Prediction Algorithm".

THANKS!  
QUESTIONS?