# Uplink User-Assisted Distributed Relaying for Cellular Communications

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# Research areas

- Research areas
  - Wireless communications, network communications
  - Signal processing, applied optimization
- Recent topics
  - MIMO precoding and capacity
  - Cognitive radio and cognitive networks
  - Cooperative communications
- Current directions
  - Future cellular systems (4G, 5G)
  - Ad hoc network communications

# Students whose work is in this talk

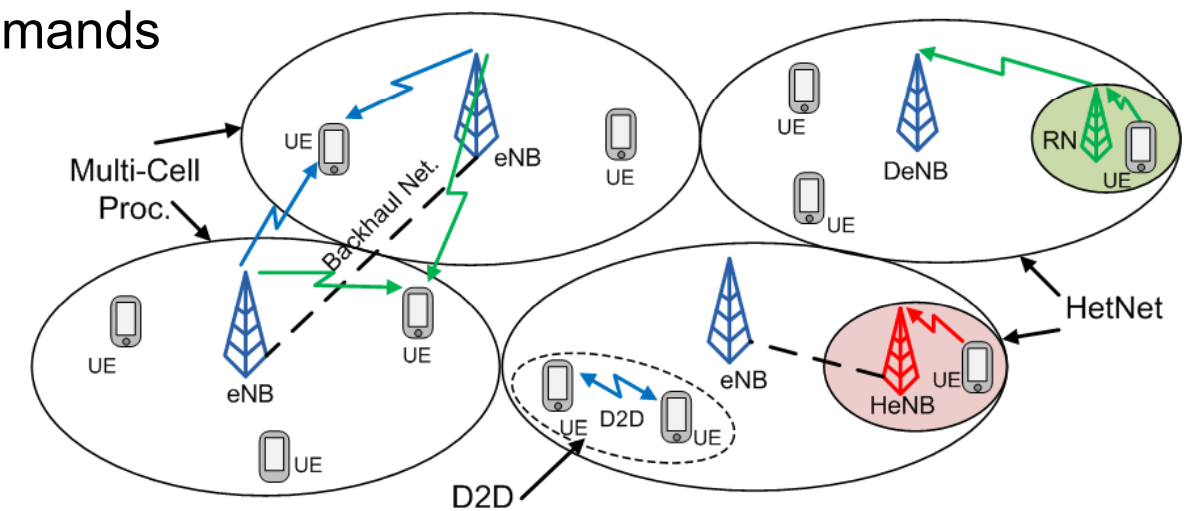
**Ahmad Abu Al Haija**

**Hussain ElKotby**

**Uplink User-Assisted Cooperative Relaying in Cellular Networks**

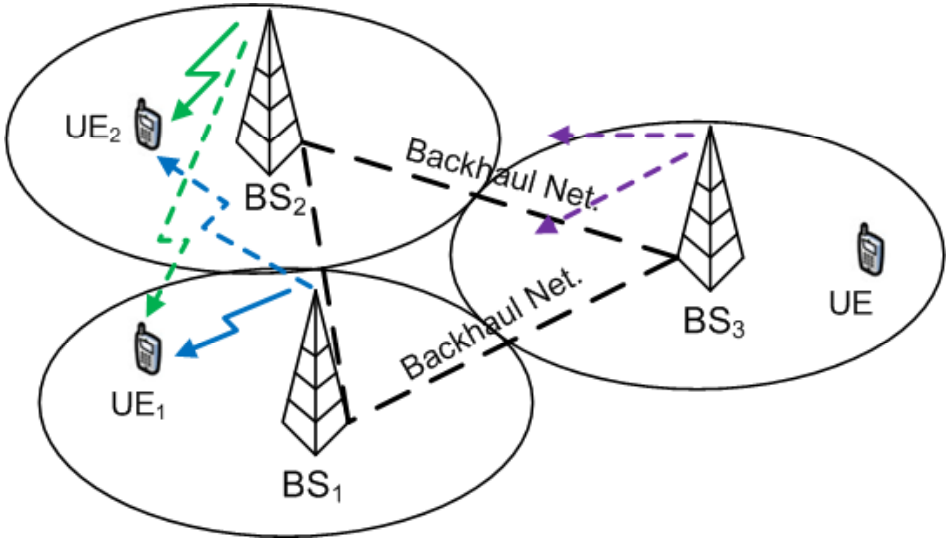
# Context

- 2G/3G cellular systems
  - Resource partitioning – connections are single-user links
  - Spectral efficiency per link approaches the theoretical limit
- Future high data rate demands
- 4G solutions
  - Small (femto) cells
  - Multi-cell processing
  - D2D communication
- 5G ideas
  - More small cells (HetNets)
  - mmWave
  - Massive MIMO
  - Smarter devices



# Multi-cell Processing / Cooperation

- The BSs are connected via Backhaul networks.
- CoMP:
  - BSs share channel state information (CSI)
  - Perform beamforming and power control
  - Downlink cooperation among BSs

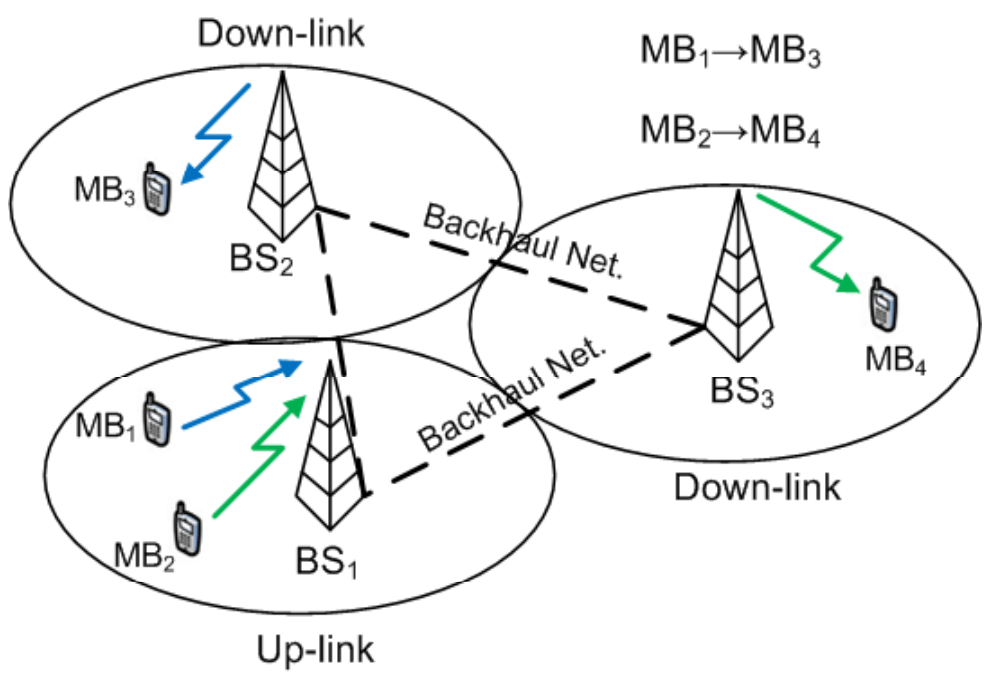



- **What about uplink cooperation among UEs?**

# Hybrid D2D-infrastructure cooperation

- Uplink communications
  - Two close UEs (mobiles) can “hear” each other
  - They can communicate directly (D2D)

  or
  - Exchange their information and perform uplink beamforming (hybrid)

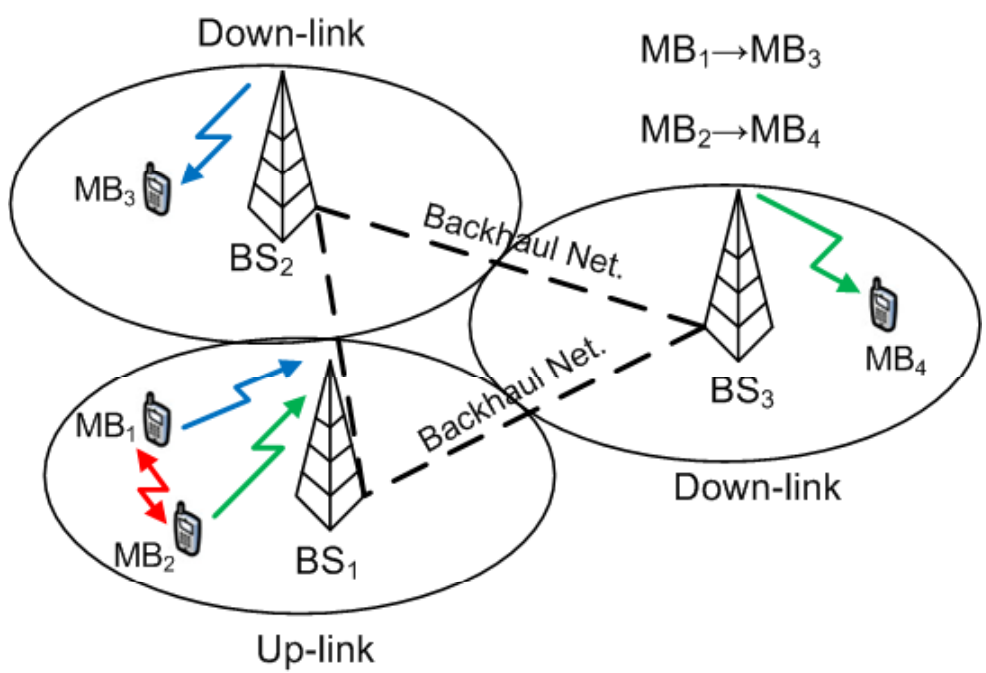


# Hybrid D2D-infrastructure cooperation

- Uplink communications
  - Two close UEs (mobiles) can "hear" each other
  - They can communicate directly (D2D)

  or
  - Exchange their information and perform uplink beamforming (hybrid)

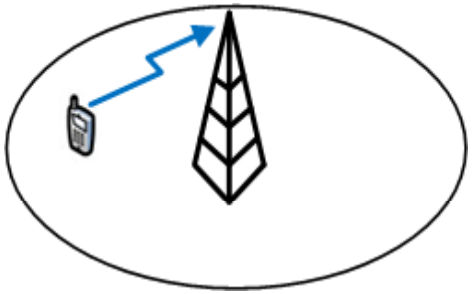
Can be applied in small cells / HetNets as well



# Comparison among 3 transmission modes

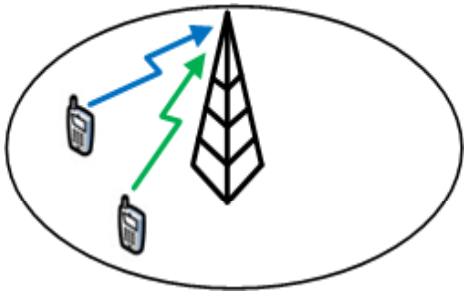
- Half-duplex transmissions
- Consider transmissions on the same frequency band

Resource partitioning
(LTE and LTE-A)



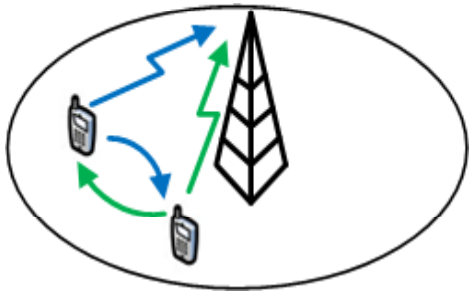
- Each UE transmits on a different time slot

Concurrent trans.
with SIC



- Both UEs transmit at the same time
- BS performs SIC

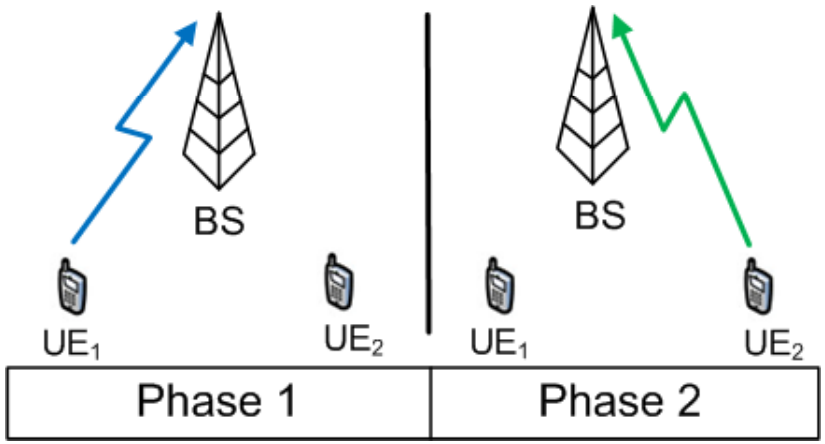
Cooperative trans.
(TD and D2D)



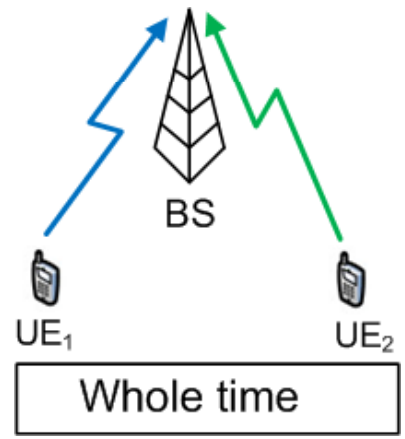
- Two UEs cooperate to transmit to the BS.
- 3 phase transmission
- Virtual beamforming
- Advance processing

# 3 transmission modes over a frame

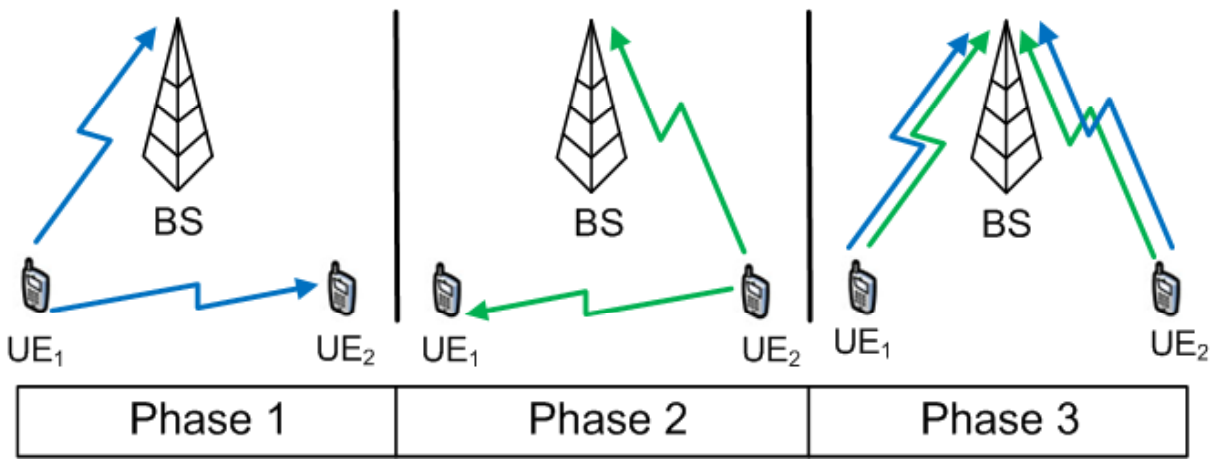
Resource partitioning (LTE and LTE-A)




Concurrent trans. with SIC



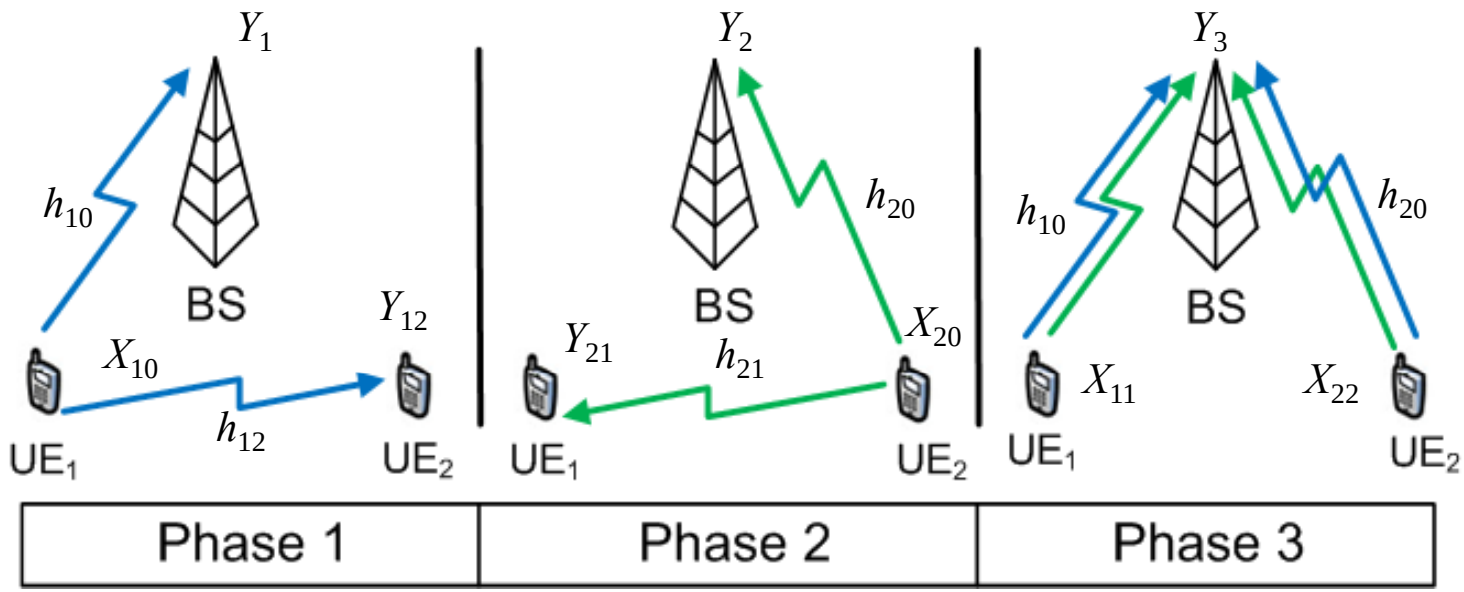

Cooperative transmission (TD and D2D)



# Outline for the rest of the talk

- User-assisted cooperative transmission
  - Transmit signal design
  - Decoding techniques
  - Achievable rate region
- Deployment in cellular networks
- Reliability/Outage performance

# Channel Model




$$Y_{12} = h_{12}X_{10} + Z_1$$
$$Y_1 = h_{10}X_{10} + Z_{31}$$

$$Y_{21} = h_{21}X_{20} + Z_2$$
$$Y_2 = h_{20}X_{20} + Z_{32}$$

$$Y_3 = h_{10}X_{11} + h_{20}X_{22} + Z_{33}$$

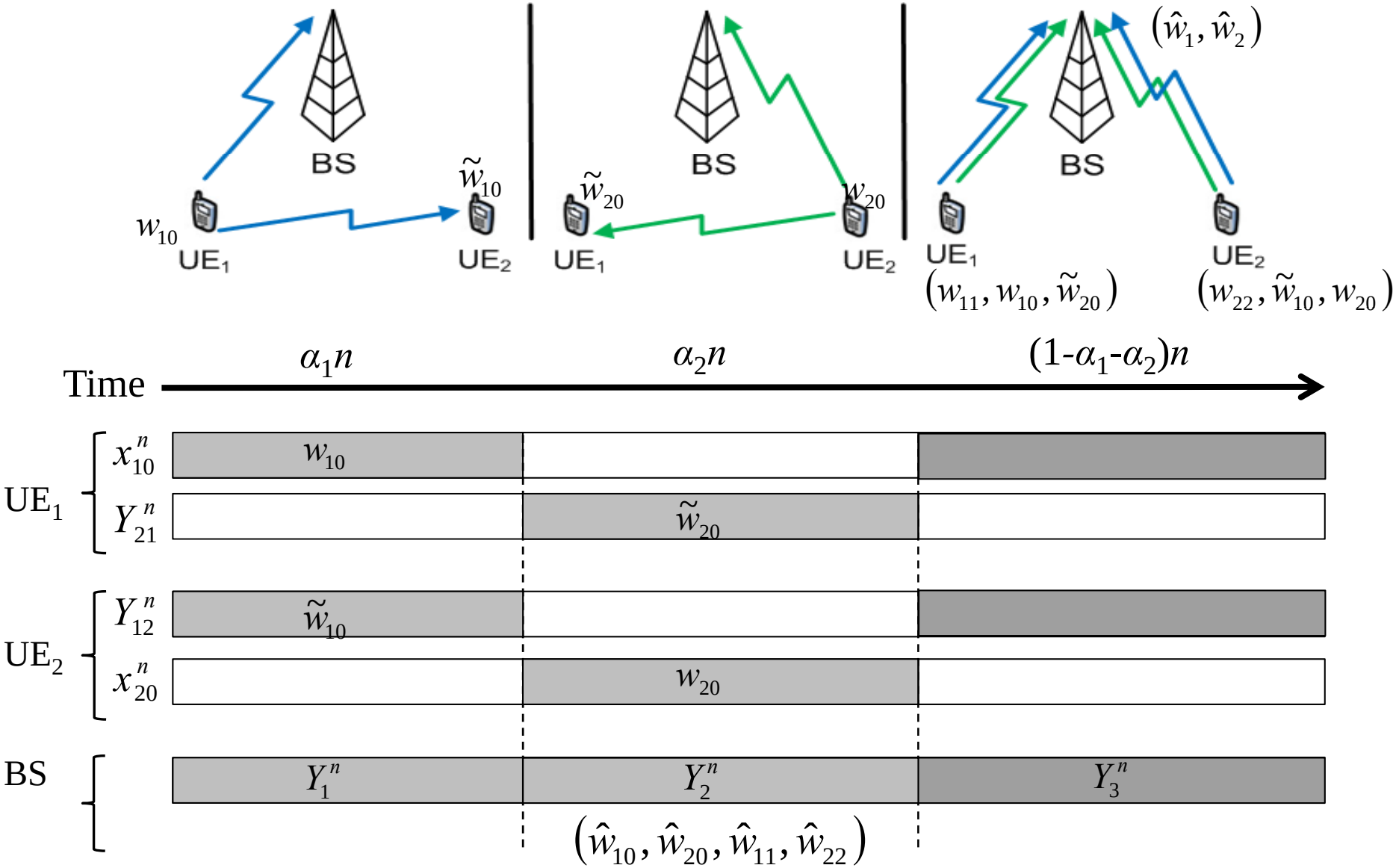
Rayleigh block fading

$$h_{ij} = g_{ij}e^{\kappa\theta_{ij}}$$

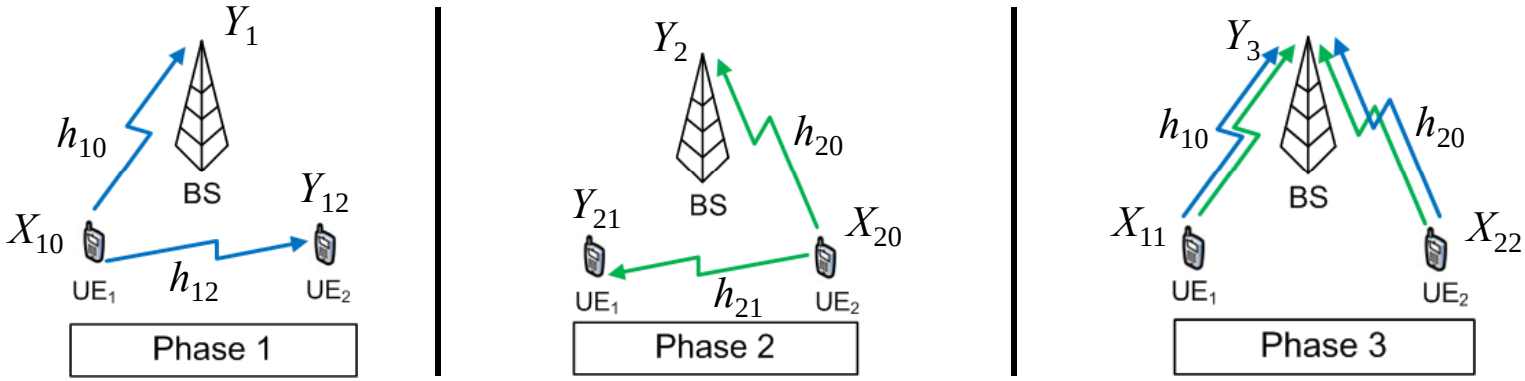
Complex Gaussian noise

$$Z \sim \mathcal{CN}(0,1)$$

# Transmission Scheme $w_1 \to (w_{10}, w_{11})$ $w_2 \to (w_{20}, w_{22})$



# Transmit signal design




**Transmit signals**

$$X_{10} = \sqrt{\rho_{10}} U_{10}(w_{10}) \qquad X_{20} = \sqrt{\rho_{20}} U_{20}(w_{20})$$

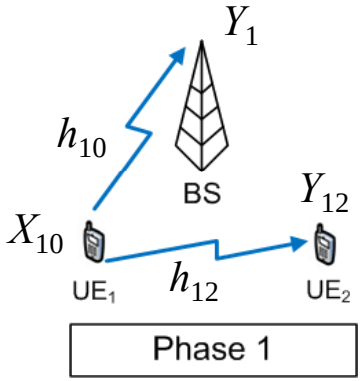
$$X_{11} = \sqrt{\rho_{11}} V_{11}(w_{11}) + \sqrt{\rho_1} S(w_{10}, w_{20})$$

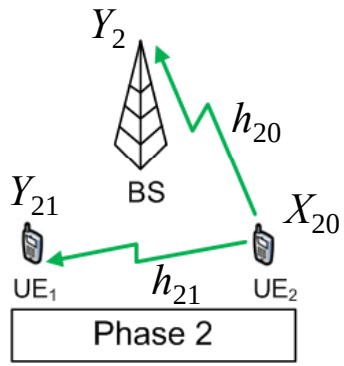
$$X_{22} = \sqrt{\rho_{22}} V_{22}(w_{22}) + \sqrt{\rho_2} S(w_{10}, w_{20})$$

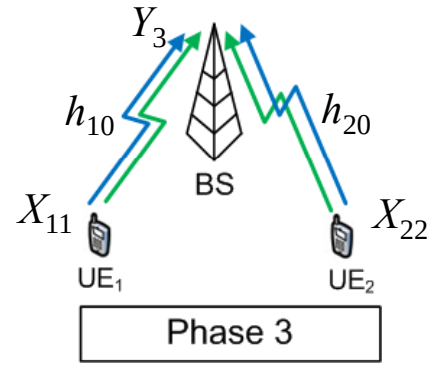
**Power constraints**

$$\alpha_1 \rho_{10} + \alpha_3(\rho_{11} + \rho_1) \leq P_1, \quad \alpha_2 \rho_{20} + \alpha_3(\rho_{22} + \rho_2) \leq P_2$$

# Decoding and Rate region




At **UE$_2$**: $Y_{12} \to \tilde{w}_{10}$

$$R_{12} \leq \alpha_1 \mathcal{C}\left(g_{12}^2 \rho_{10}\right) = J_1$$

At **UE$_2$**: $Y_{21} \to \tilde{w}_{20}$

$$R_{21} \leq \alpha_1 \mathcal{C}\left(g_{21}^2 \rho_{20}\right) = J_2$$

At **BS**: $(Y_1, Y_2, Y_3) \to (\hat{w}_1, \hat{w}_2)$

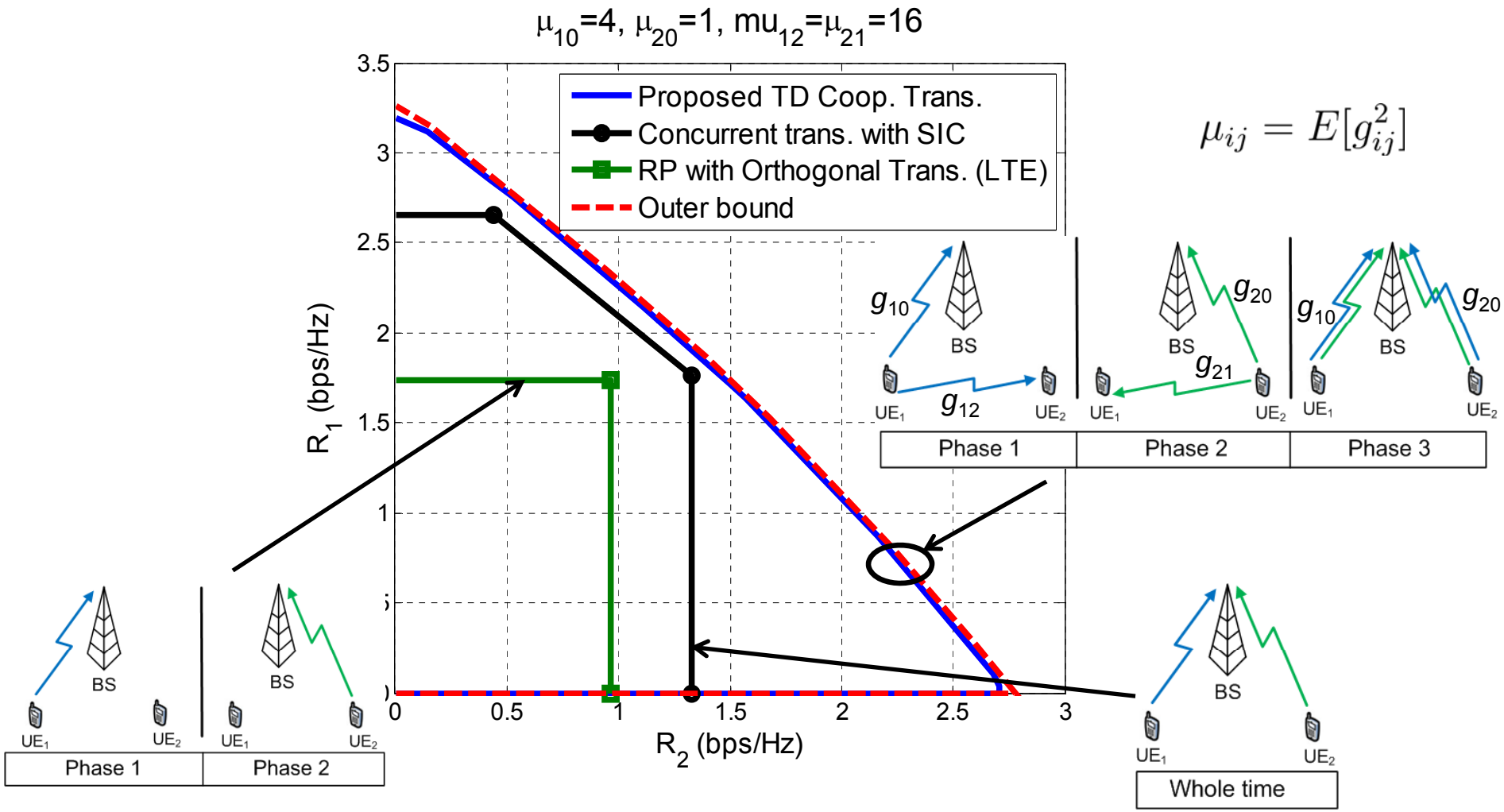
$$R_{11} \leq \alpha_3 \mathcal{C}\left(g_{10}^2 \rho_{11}\right) = J_3, \qquad R_{22} \leq \alpha_3 \mathcal{C}\left(g_{20}^2 \rho_{22}\right) = J_4,$$

$$R_{11} + R_{22} \leq \alpha_3 \mathcal{C}\left( \qquad R_1 \leq J_1 + J_3, \qquad R_2 \leq J_2 + J_4\right.$$

$$R_1 + R_{22} \leq \alpha_1 \mathcal{C}\left( R_1 + R_2 \leq J_1 + J_2 + J_5, \quad R_1 + R_2 \leq J_8 \qquad J_7\right.$$

$$R_1 + R_2 \leq \alpha_1 \mathcal{C}\left(g_{10}^2 \rho_{11}\right) + \alpha_2 \mathcal{C}\left(g_{20}^2 \rho_{20}\right) + \alpha_3 \zeta = J_8, \quad \zeta = \mathcal{C}\left(g_{10}^2 \rho_{11} + g_{20}^2 \rho_{22} + \left(g_{10}\sqrt{\rho_1} + g_{20}\sqrt{\rho_2}\right)^2\right).$$

# Achievable Rate Region




A. Abu Al Haija and M. Vu, "**A Half-Duplex Cooperative Scheme with Partial Decode-Forward Relaying**" IEEE Int'l Symp. on Information Theory, July 2011.

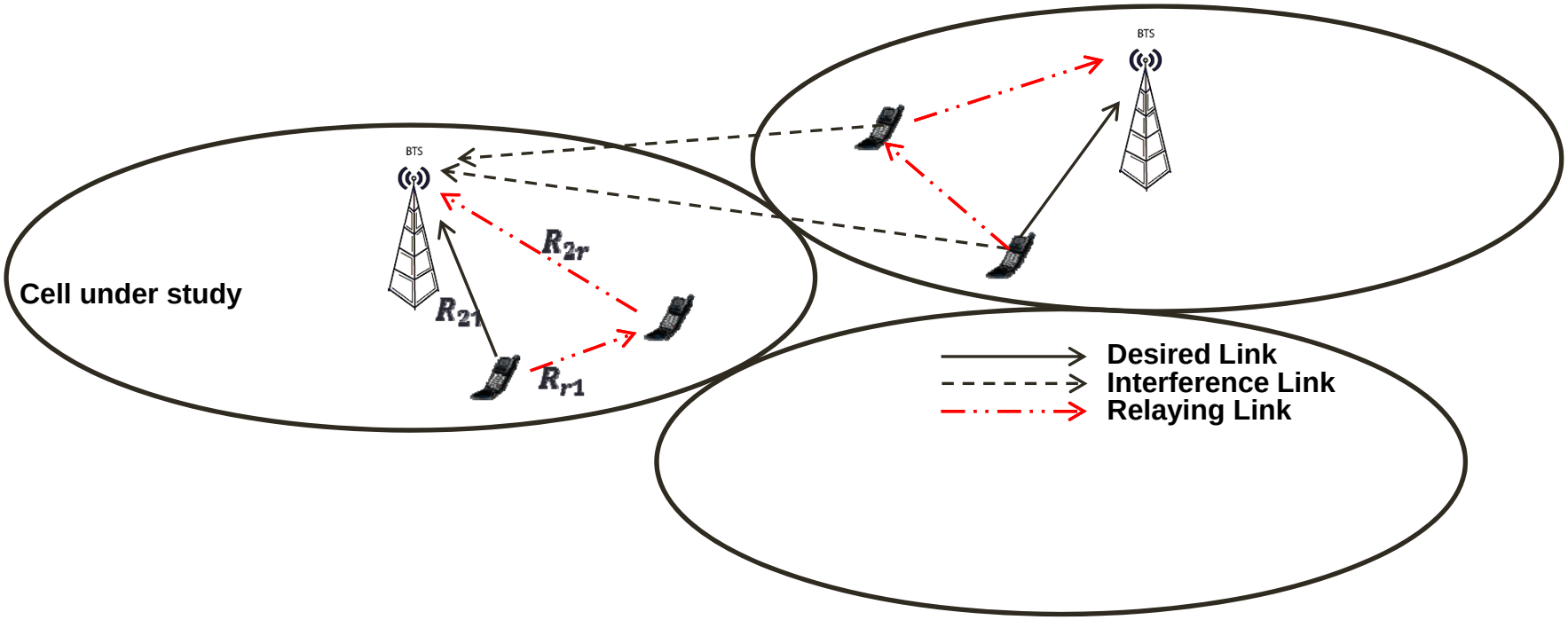
# Talk Outline

- User-assisted cooperative transmission

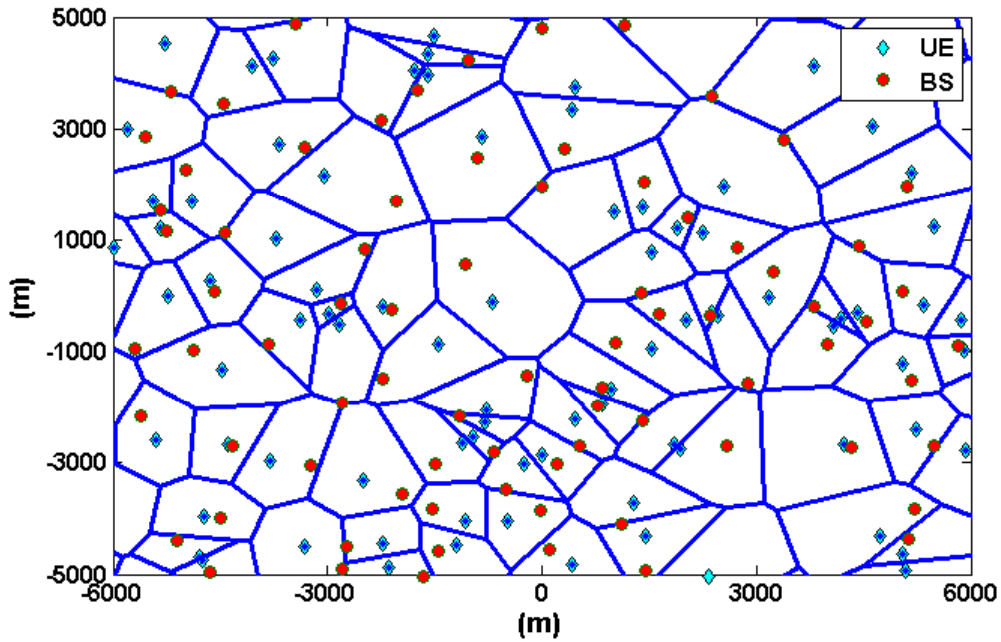
- Deployment in cellular networks
  - Deployment policy
  - Out-of-cell interference
  - Throughput performance gain
- Reliability/Outage performance

# Deployment in Cellular Networks

- Deployment of user-assisted relaying
  - An idle user helps relay data of an active user
- Study **network-wide impact** of user-assisted relaying
  - On throughput, outage, coverage

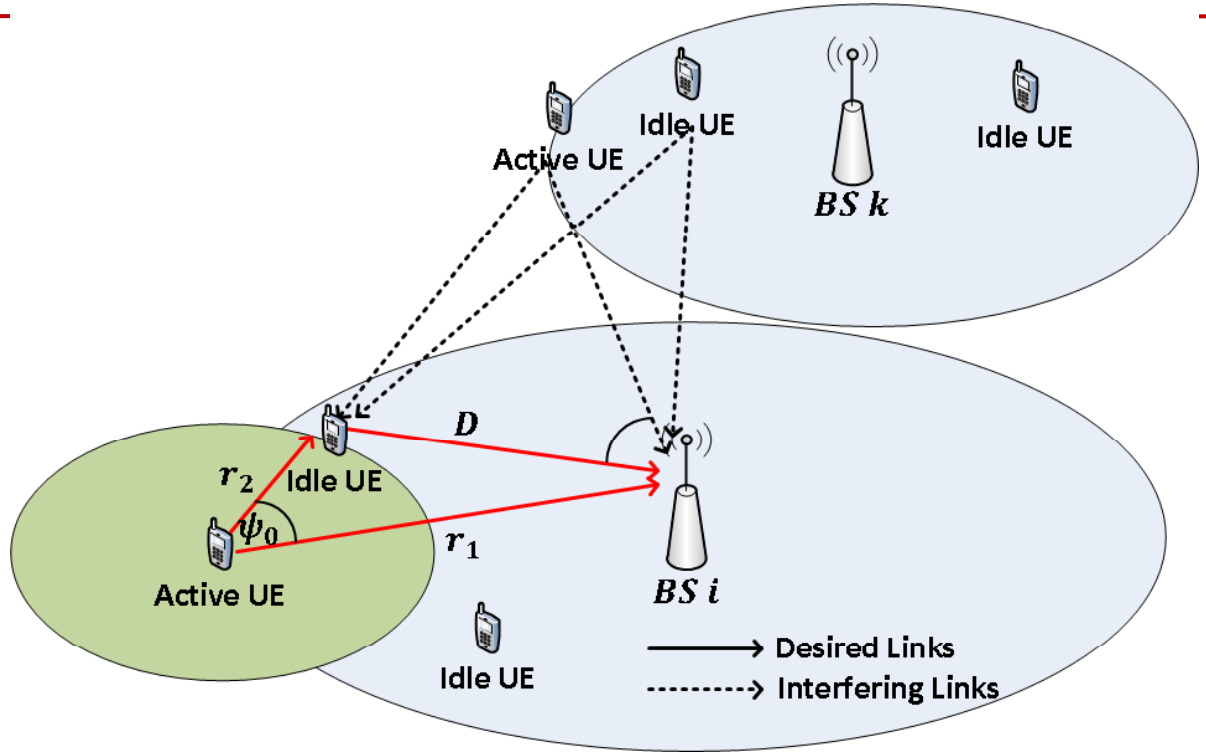


# Stochastic Geometry Model




- Factors to consider:
  - When should a user cooperate?
  - What is the effect on network interference and overall performance?
- Performance evaluation:
  - Analysis using stochastic geometry tools
  - Verify analysis with simulation

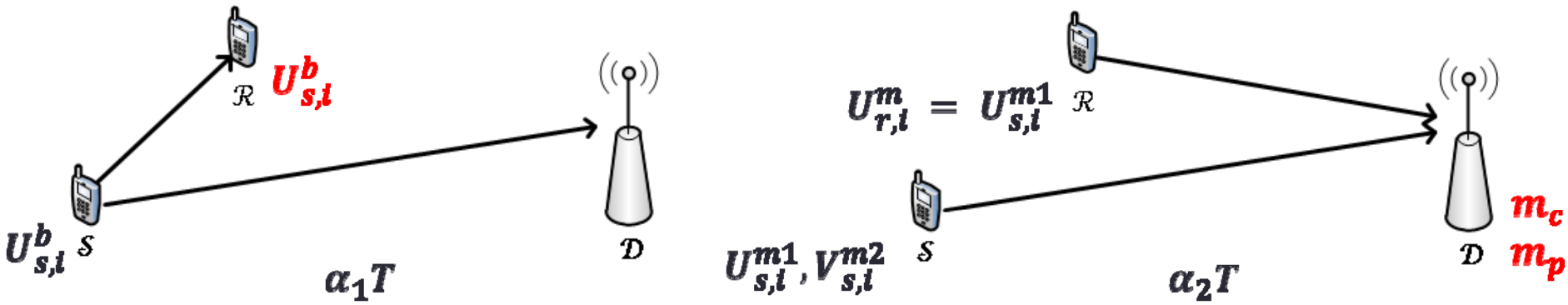
# System Model




- Consider a multi-cell system
  - Each cell has a single base station
  - Reuse factor 1 in the whole network
  - An active user can relay through the closest idle user

# Channel Model & Relaying Scheme

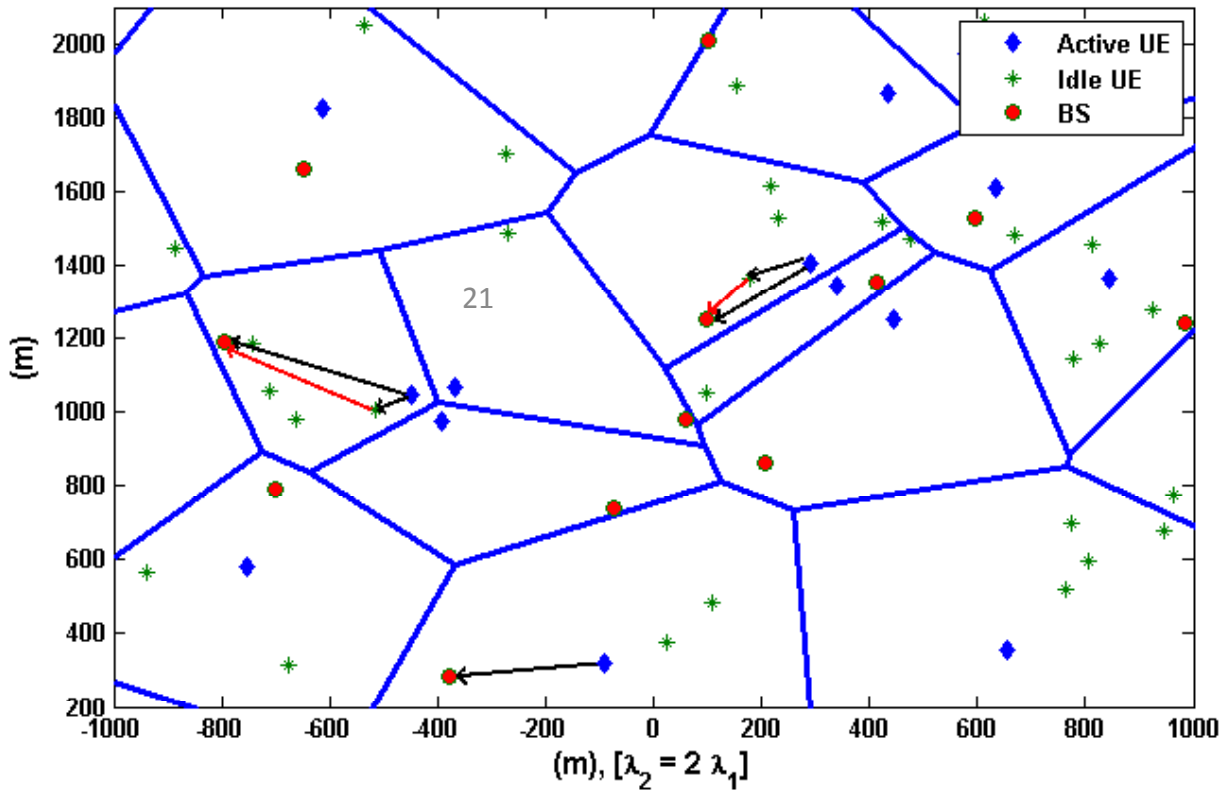
$T$: Transmission Time $\qquad \alpha_1, \alpha_2 \in [0,1], \alpha_1 + \alpha_2 = 1$




- User-assisted relaying:
  - Two phase transmission scheme
  - Flat fading over the two phase period
- **Active user (source S)**: uses superposition coding
- **Relay user (relay R)**: transmit coherently with the source in 2nd phase
- **Base station (destination D)**: utilizes received signals in both phases to decode the message

# Network Geometric Model

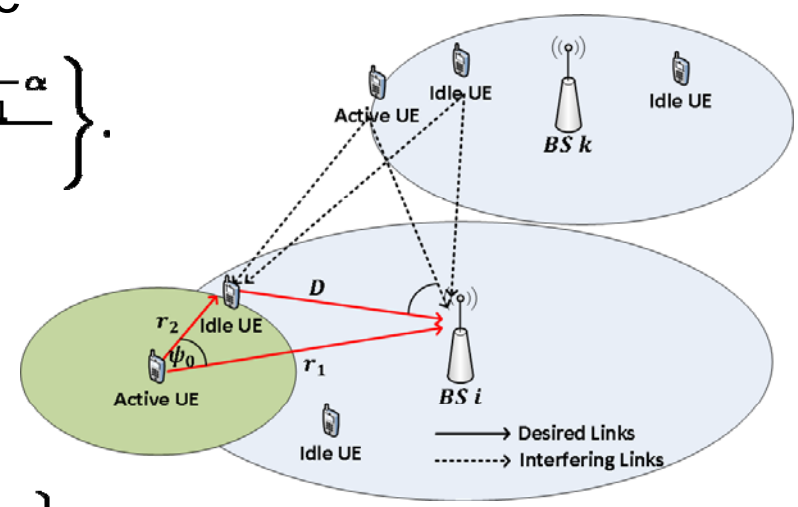
- We use stochastic geometry to model the network
- Active UEs as a PPP with density $\lambda_1$
- Idle UEs as a PPP with density $\lambda_2$



# Cooperation Policies

- Ideal policy ($E_1$):
  - Perfect knowledge of source channel state information
  - Perfect knowledge of the interference

$$E_1 \simeq \left\{ \frac{g_{sr} r_2^{-\alpha}}{\mathcal{I}_r^2} \geq \frac{g_{sd} r_1^{-\alpha}}{\mathcal{I}_d^2} \right\}.$$



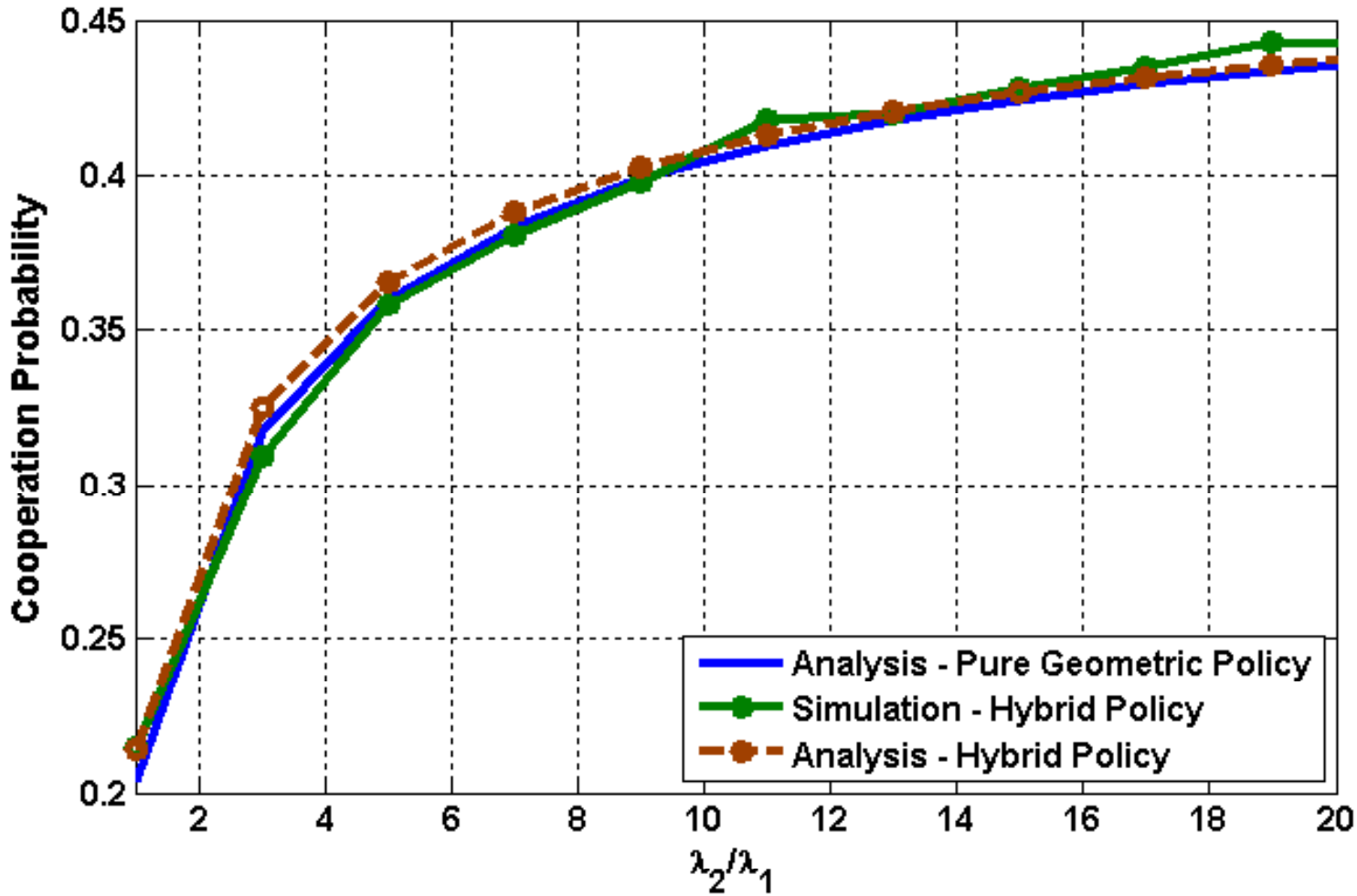

- Pure geometric policy ($E_2$):
  - Only knows the distances
  - Practical for fast fading channels

$$E_2 = \{r_1 \geq r_2, D \leq r_1\}.$$

- Hybrid fading and geometric policy ($E_3$):
  - Knows both small and large scale fading but not the interference
  - Applicable for slow fading channels

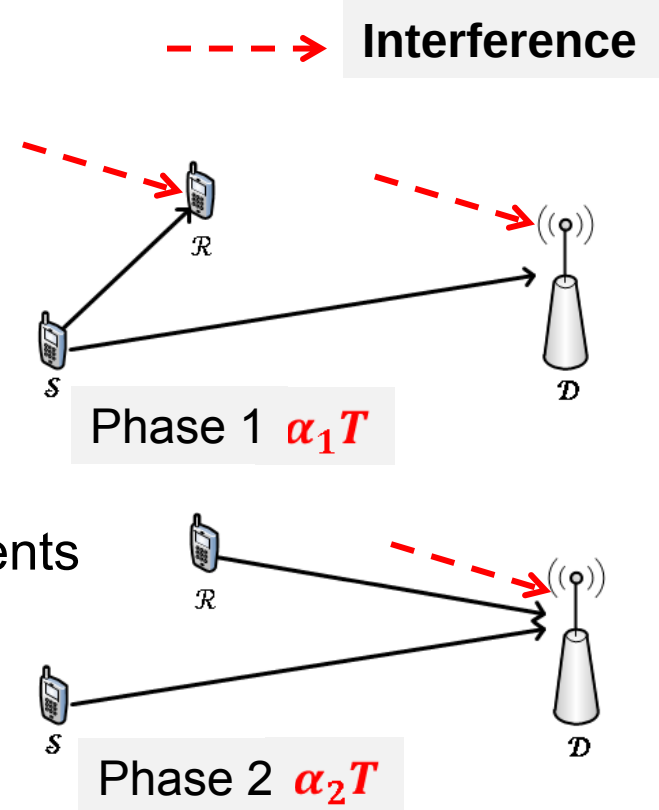
$$E_3 = \{g_{sd} r_1^{-\alpha} \leq g_{sr} r_2^{-\alpha}, D \leq r_1\}.$$

# Cooperation Probability

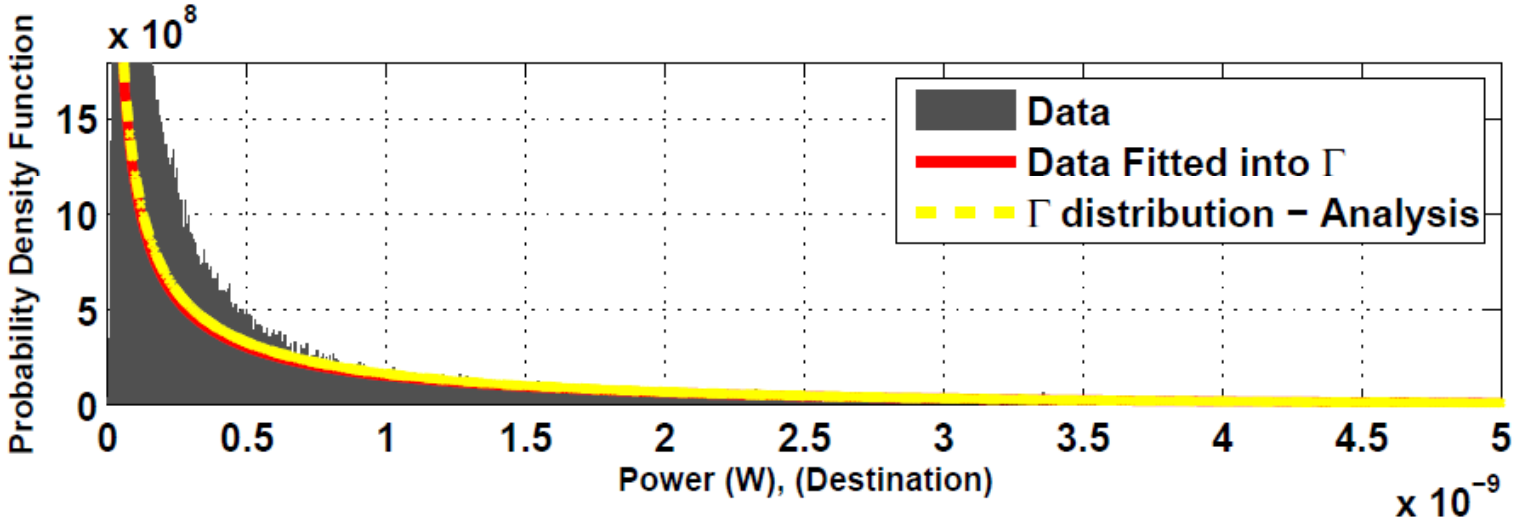


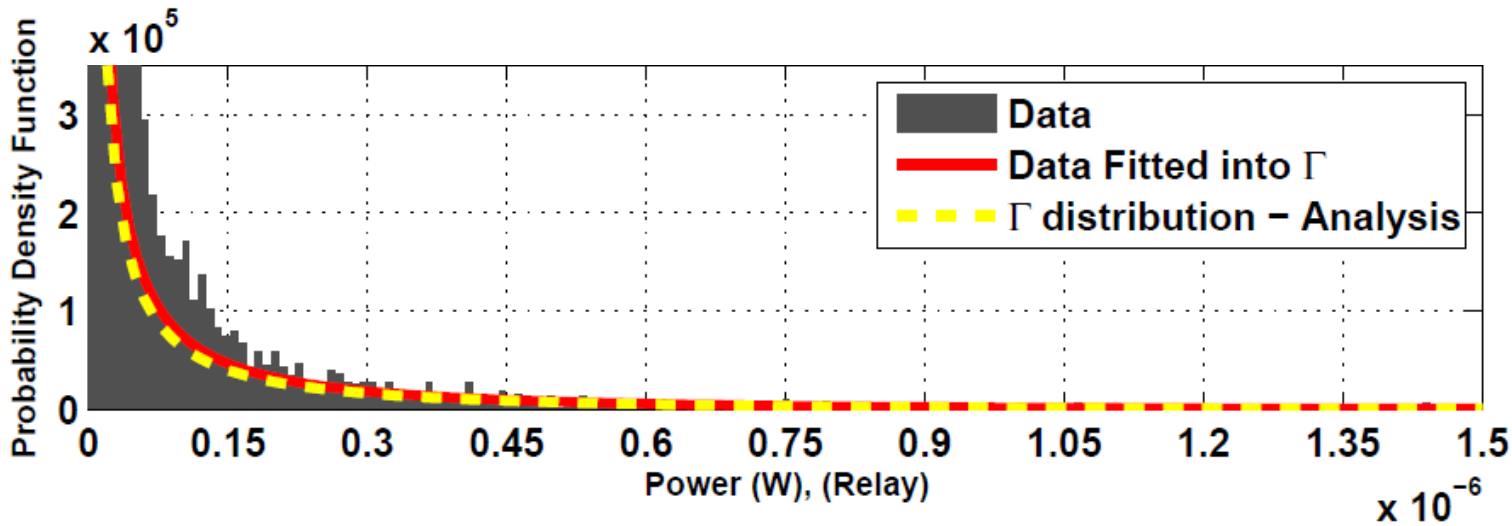
# Interference Model

- We need to characterize the interference at
  - Relay user during 1st phase
  - Base station during 1st phase
  - Base station during 2nd phase
- Stochastic geometry and PPP
  - Can provide analytic expression for moments
  - Fails to provide the exact distribution
- Consider a Gamma distribution model
  - Fit the first two moments of interference distribution
  - Approximately fit empirical data

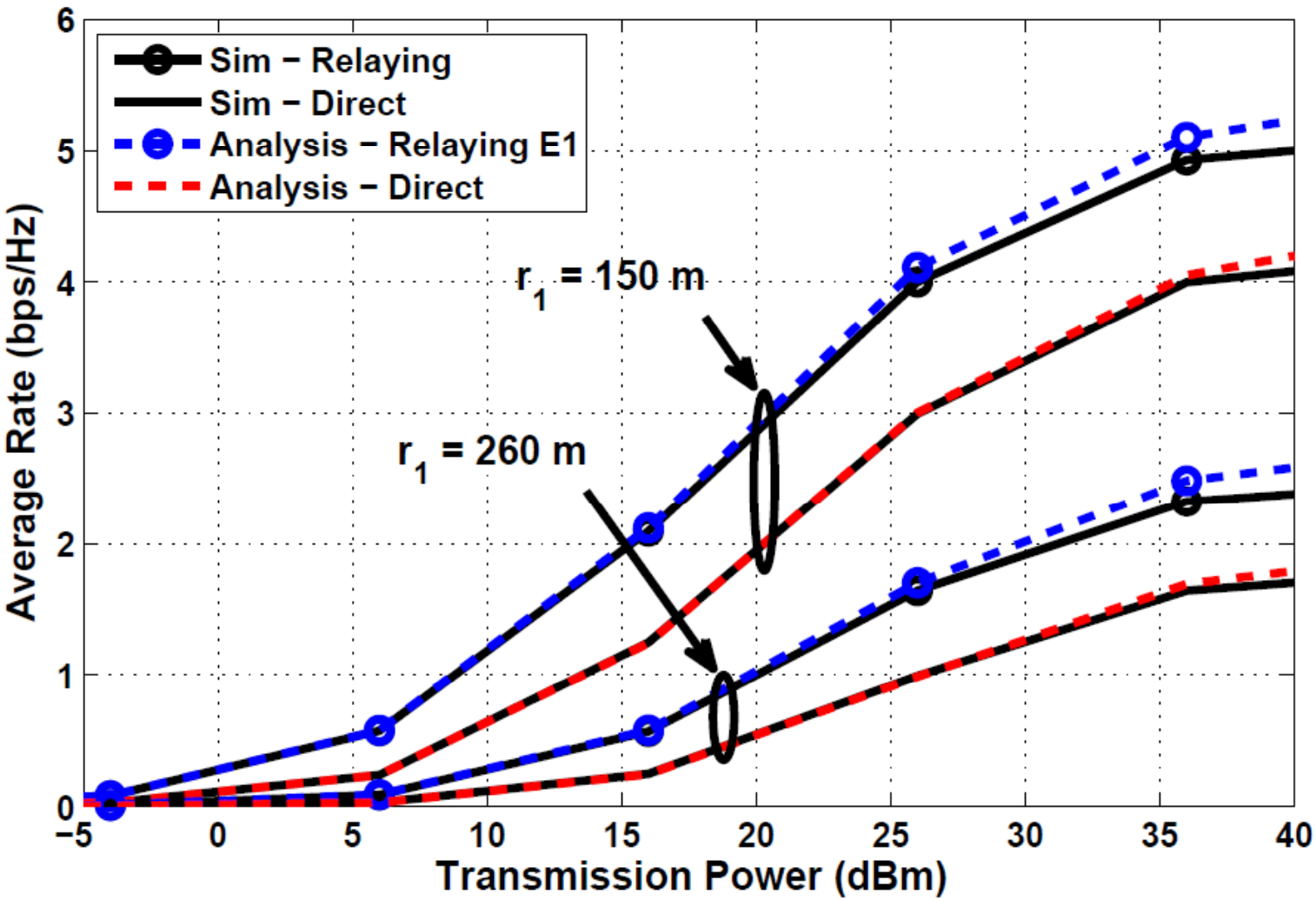


# Fit of Gamma Distribution

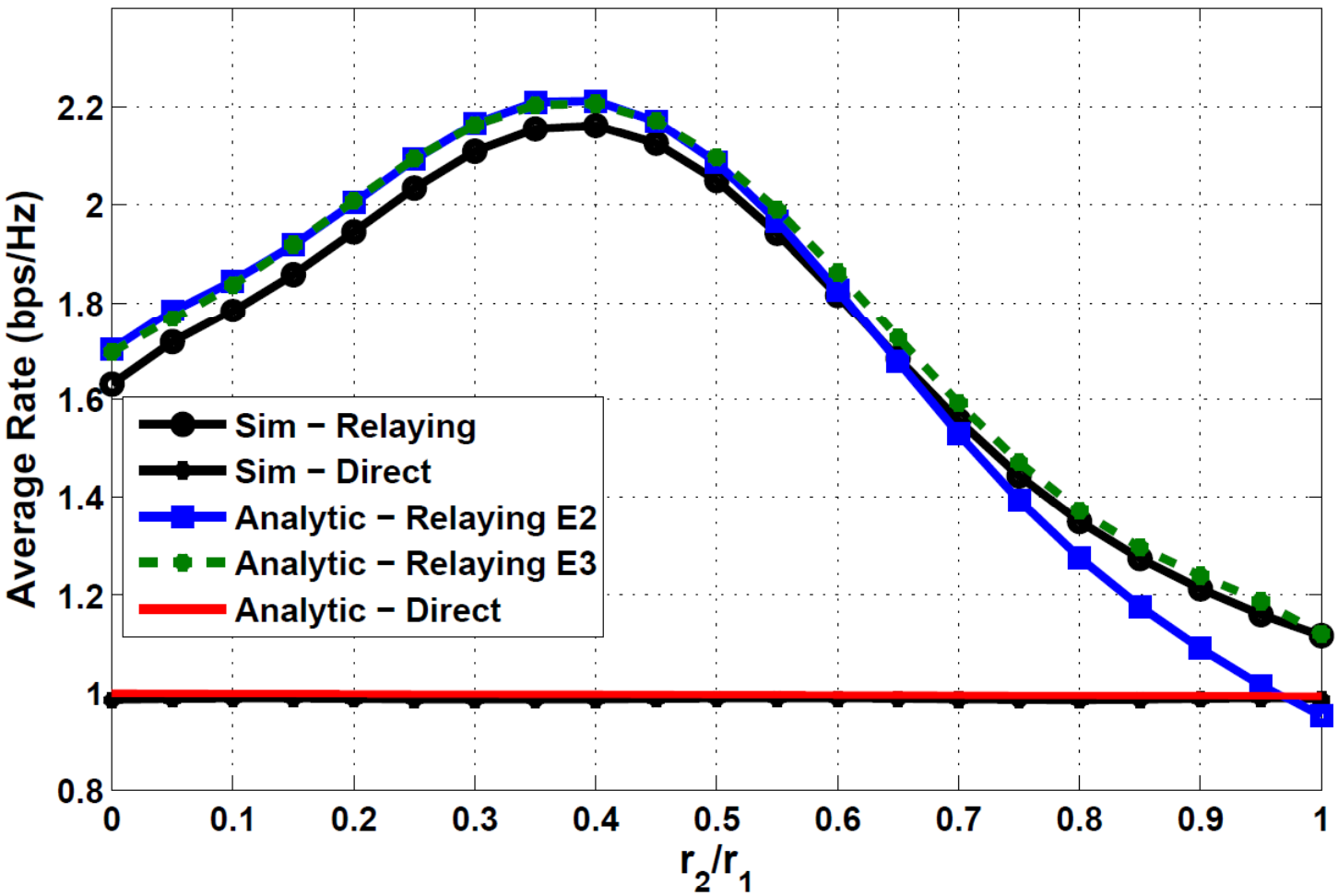


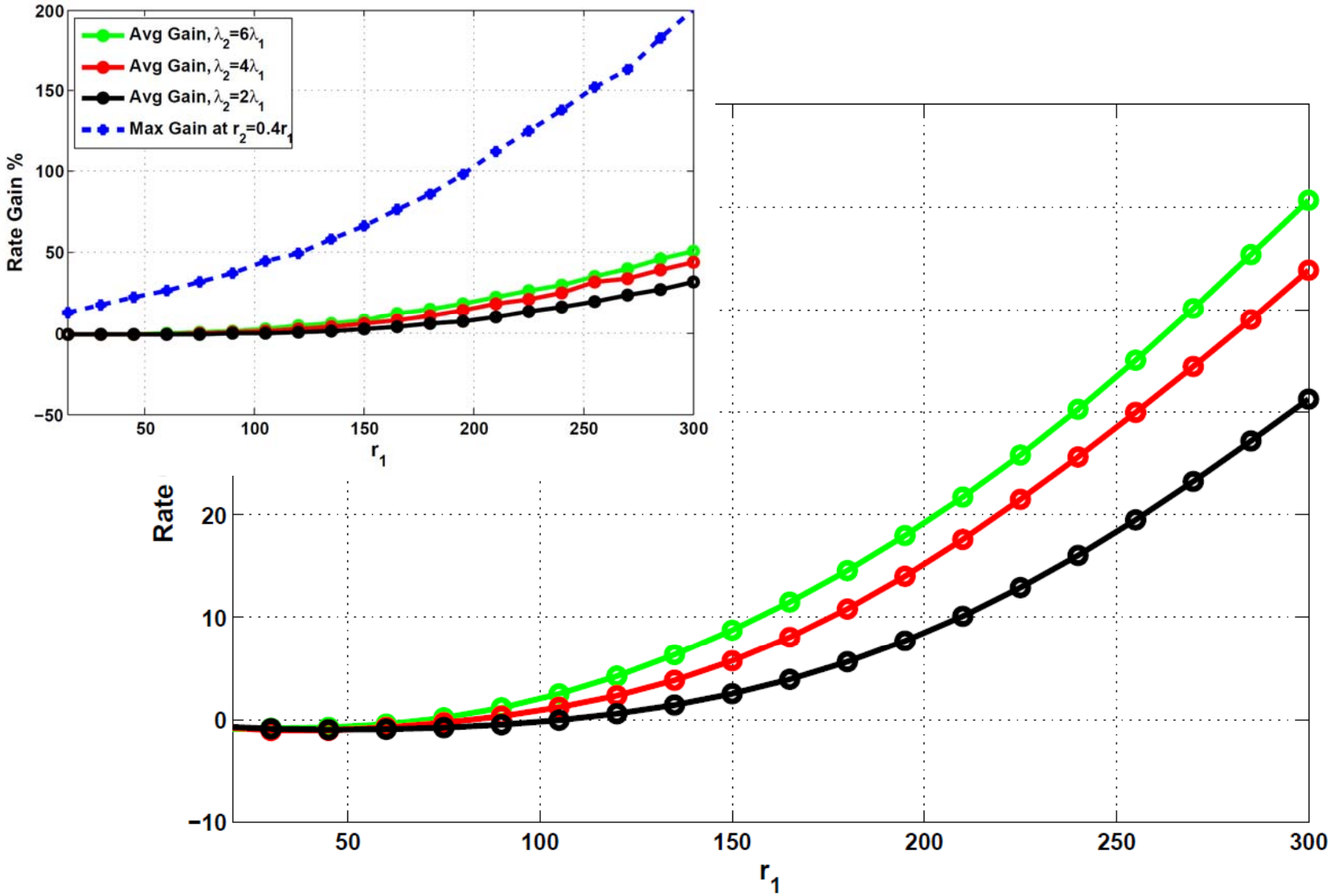
# Interference Model: Effect of Gamma Distribution



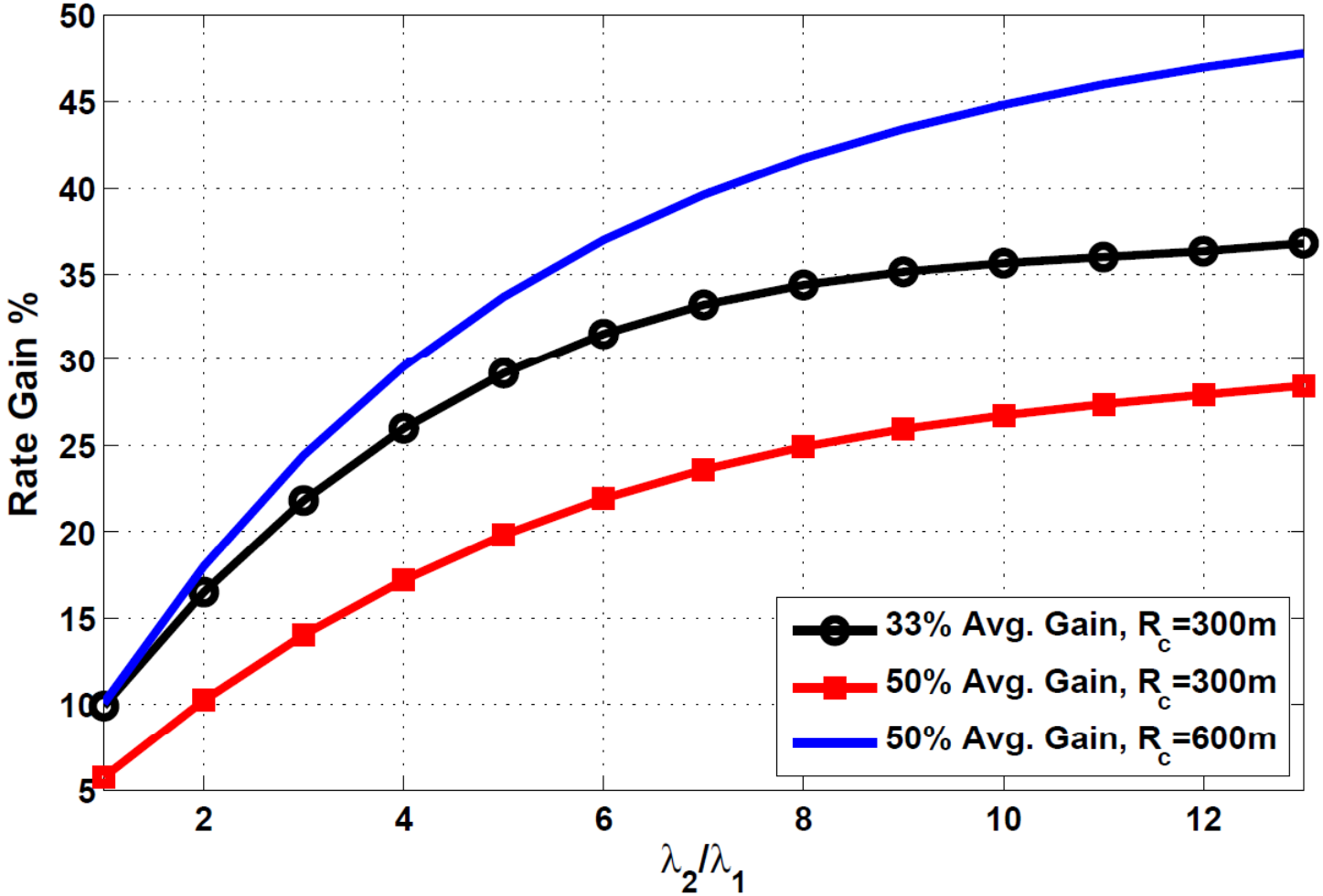
# Throughput vs. Distance to Relay



# Data rate gain vs. active user location



# Average data rate gain vs. idle to active ratio



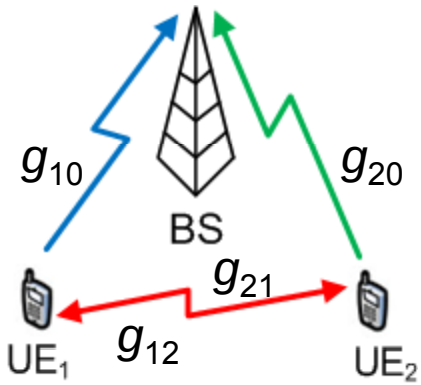

H. ElKotby and M. Vu, **"Interference and Throughput Analysis of Uplink User-Assisted Relaying in Cellular Networks,"** IEEE 25th Int'l Symp. on Personal, Indoor and Mobile Radio Commun. (PIMRC), Sep 2014.

# Talk Outline

- User-assisted cooperative transmission
- Deployment in cellular networks
- Reliability/Outage performance
  - Outage at the UEs and BS
  - Common outage
  - Individual outage

# Outage Probabilities

- Full CSI at Rx and limited at Tx.

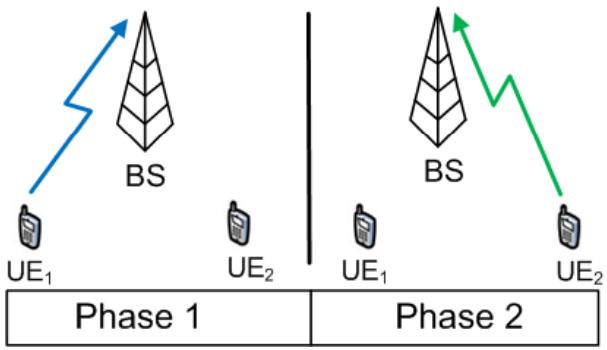



- Consider both individual and common outage probabilities
  - Common outage: either one or both UEs information is in outage.
  - Individual outage: one UE information is in outage regardless of the other UE information.

- The outage probabilities in Rayleigh fading channels

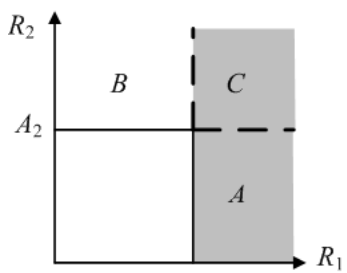
# Outage Probability: LTE and Concurrent Trans.

## LTE & LTE-A

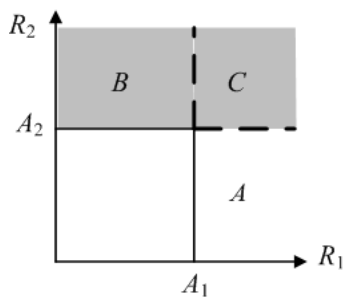



Rates: $R_1 \leq A_1,\ R_2 \leq A_2,$

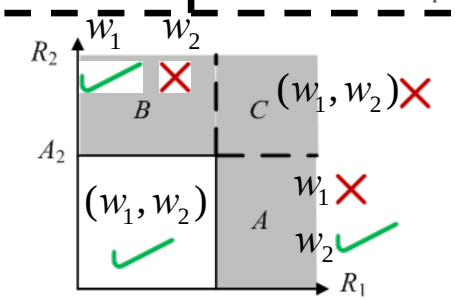
Individual Outage ($UE_1$)



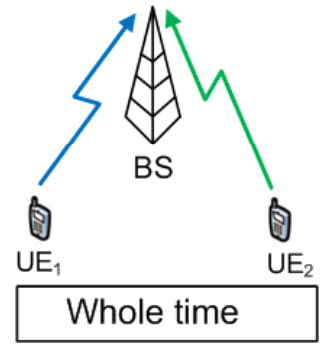

Individual Outage ($UE_2$)




Common Outage



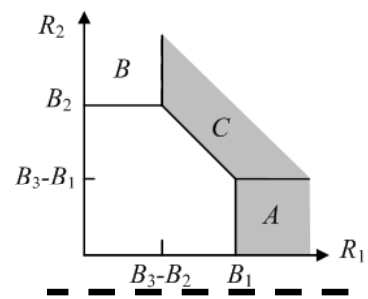

## Concurrent trans. with SIC



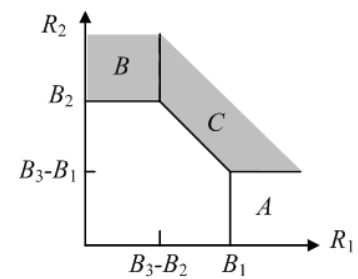

Rates: $R_1 \leq B_1,\ R_2 \leq B_2,$

$R_1 + R_2 \leq B_3$

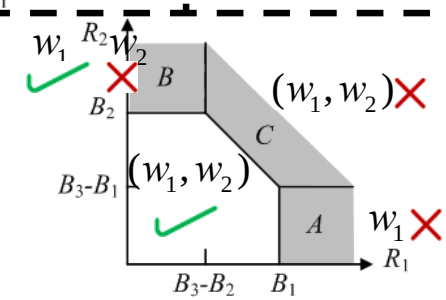
Individual Outage ($UE_1$)




Individual Outage ($UE_2$)

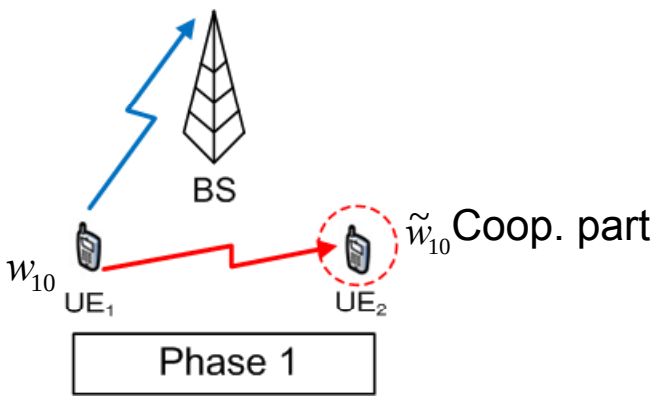



Common Outage

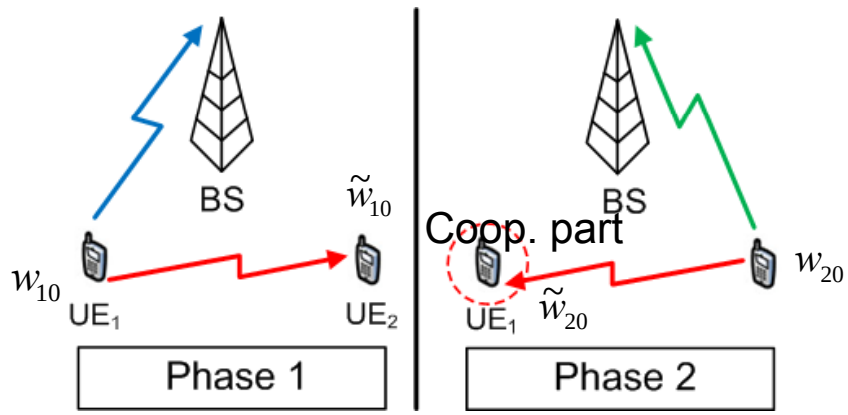


# Cooperative Transmission Outages

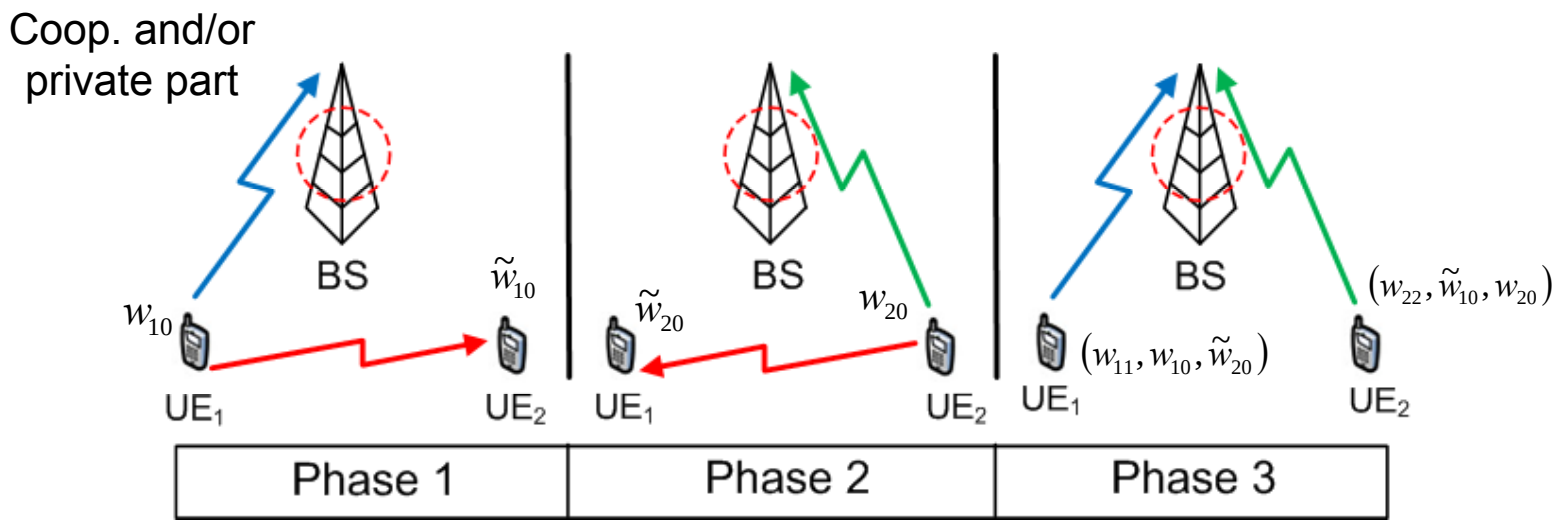
**Outage at UE2**



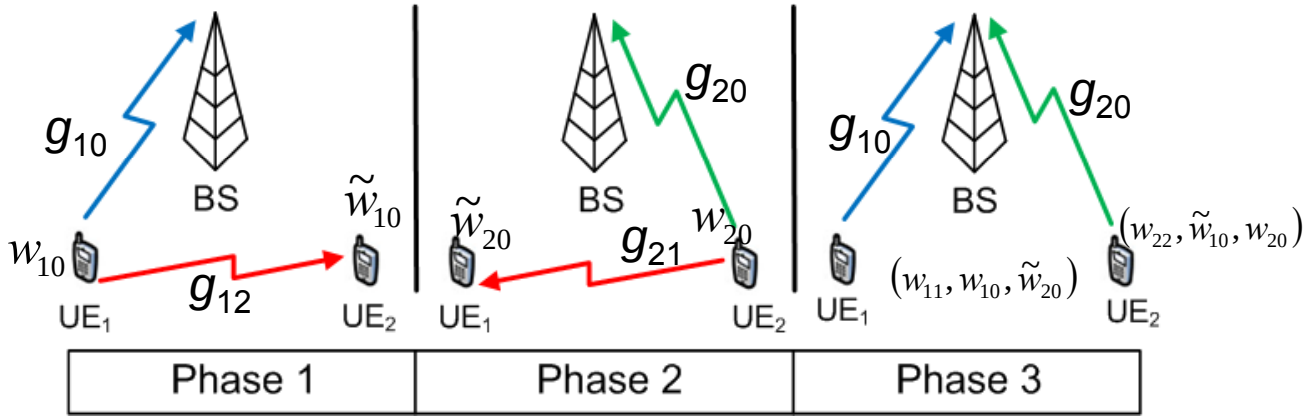

**No Outage at UE2 but at outage UE1**




**No Outage at both UEs but outage at the BS**



# Outage Analysis for Cooperative Transmission




- Outage can occur at **UEs** in addition to the BS
  - But cooperative links are stronger than direct links
  - Hence outage at UEs is small (insignificant)
  - Cooperation reduces outage probability

- Superposition coding
  - Outage for **cooperative and private** parts

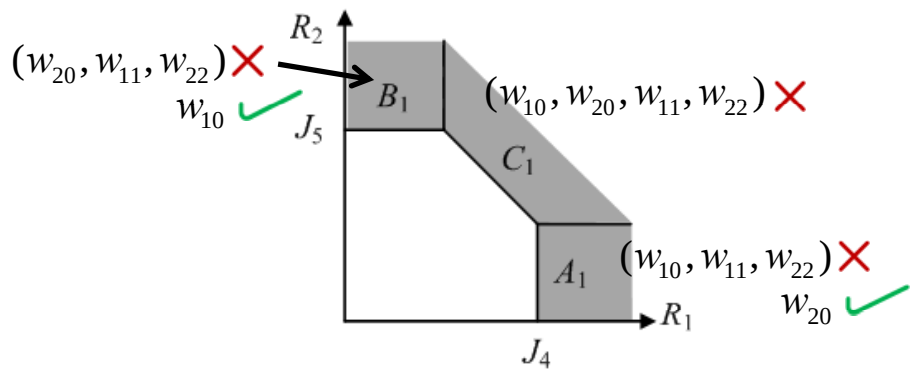
# Outage at the BS (if no outage at UEs)

$R_{10} \leq J_4 - R_p,\ R_{20} \leq J_5 - R_p,\ R_{10} + R_{20} \leq J_6 - R_p,$ Cooperative rates const.

where $R_p = R_{11} + R_{22}$

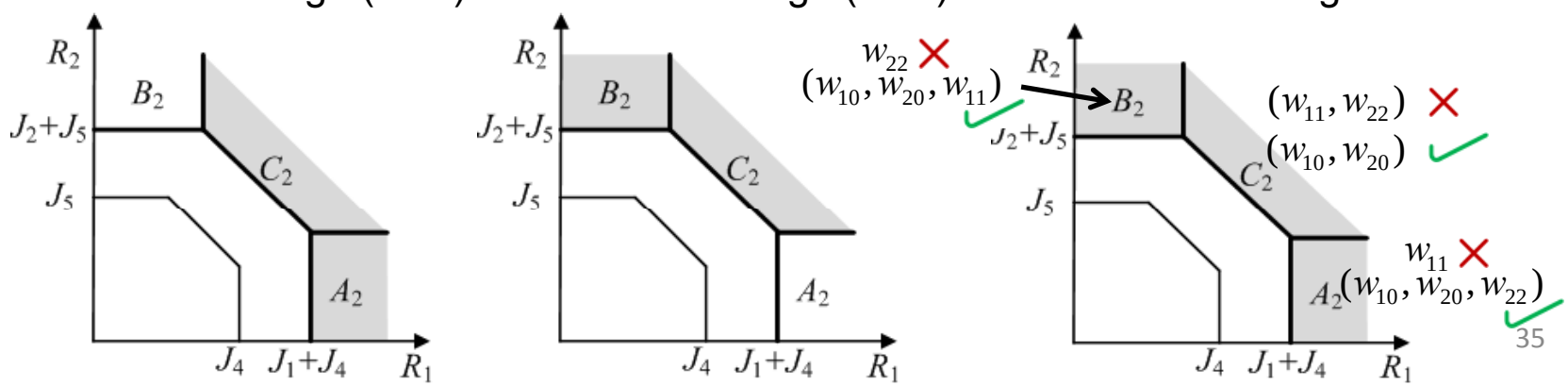
$R_{12} \leq J_1,\ R_{22} \leq J_2,\ R_{12} + R_{22} \leq J_3,$ Private rates const.

**Cooperative parts outage**: Outage of any cooperative part leads to an outage at both private parts because of superposition encoding

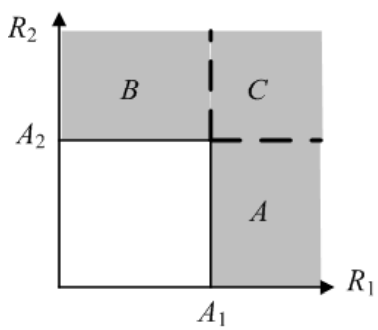
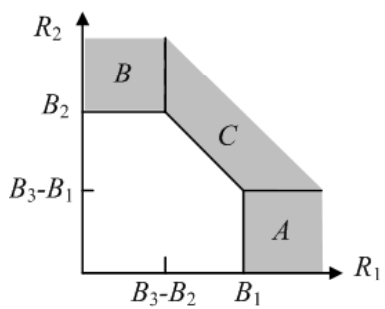
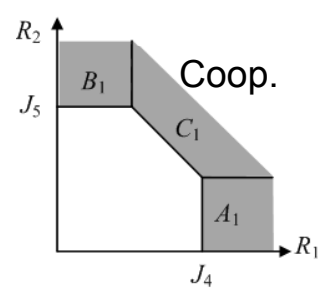
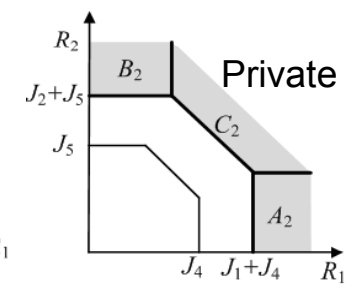



**Common and individual Outages for private parts (no outage for the coop. parts)**

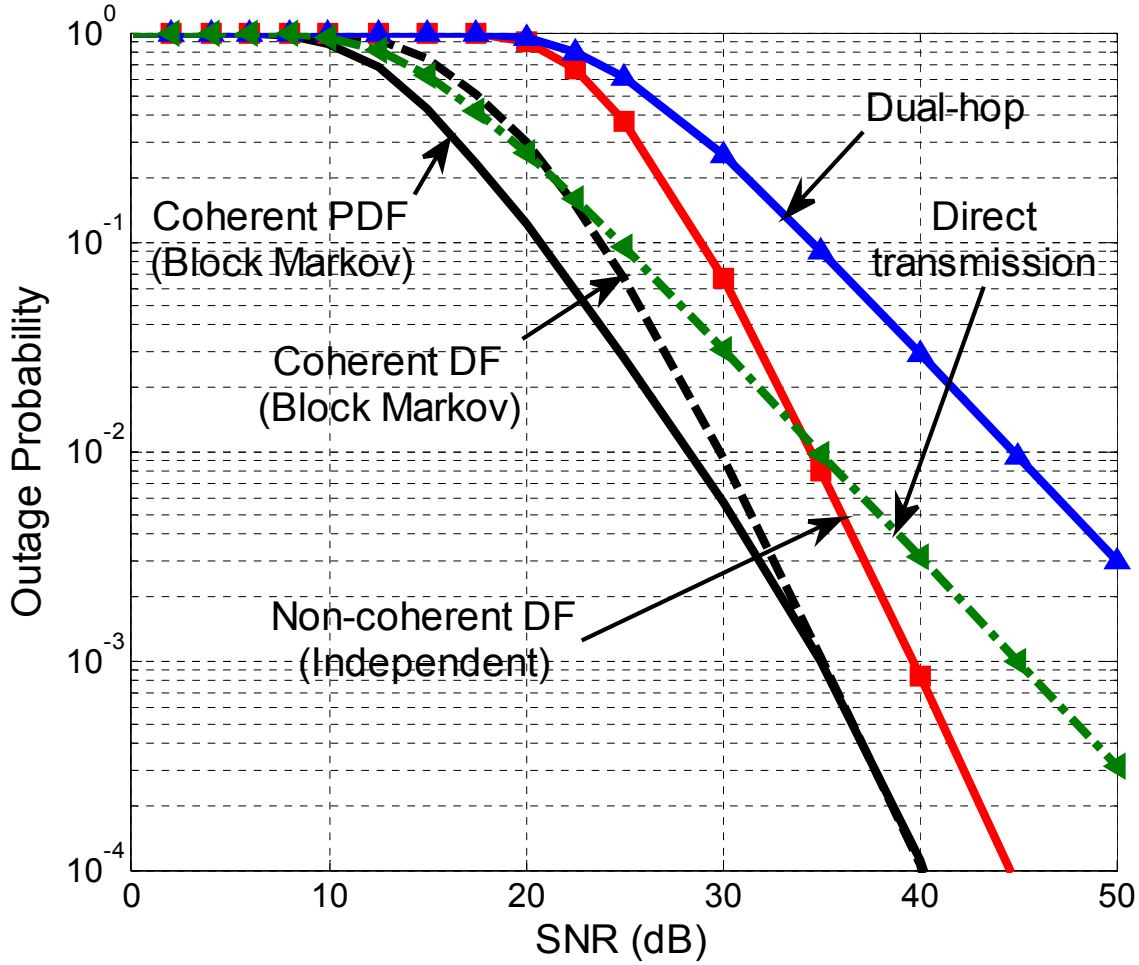
Individual Outage (UE1) Individual Outage (UE2) Common Outage

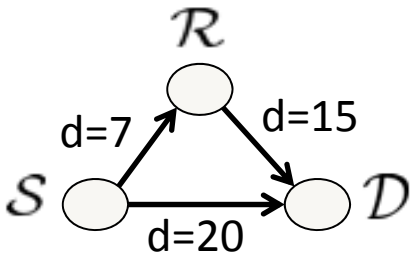


# Summary of the Outage Analyses

| *Resource Part. LTE & LTE-A | *Concurrent Trans. with SIC | *Coop. Trans. using D2D |
|---|---|---|
| • No message splitting | • No message splitting | • Coop. & private message splitting (outage for each part)<br>• Additional outage at UEs |
| • Conventional coding | • Conventional coding | • Superposition Coding |
| • Outage at the BS only | • Outage at the BS only | • Outage at the UEs & the BS |
| • Rates at BS:<br>$R_1 \leq A_1,\ R_2 \leq A_2,$<br>  <br> | • Rates at BS:<br>$R_1 \leq B_1,\ R_2 \leq B_2,$<br>$R_1 + R_2 \leq B_3$<br>  <br> | • Outage at UE1 or UE2 leads to a common outage<br>• No outage at UEs but at BS<br>• Coop. Rates<br>$R_{10} \leq J_4,\ R_{20} \leq J_5,\ R_{10} + R_{20} \leq J_6,$<br>• Private Rates<br>$R_{12} \leq J_1,\ R_{22} \leq J_2,\ R_{12} + R_{22} \leq J_3,$<br>  <br><br>  <br> |

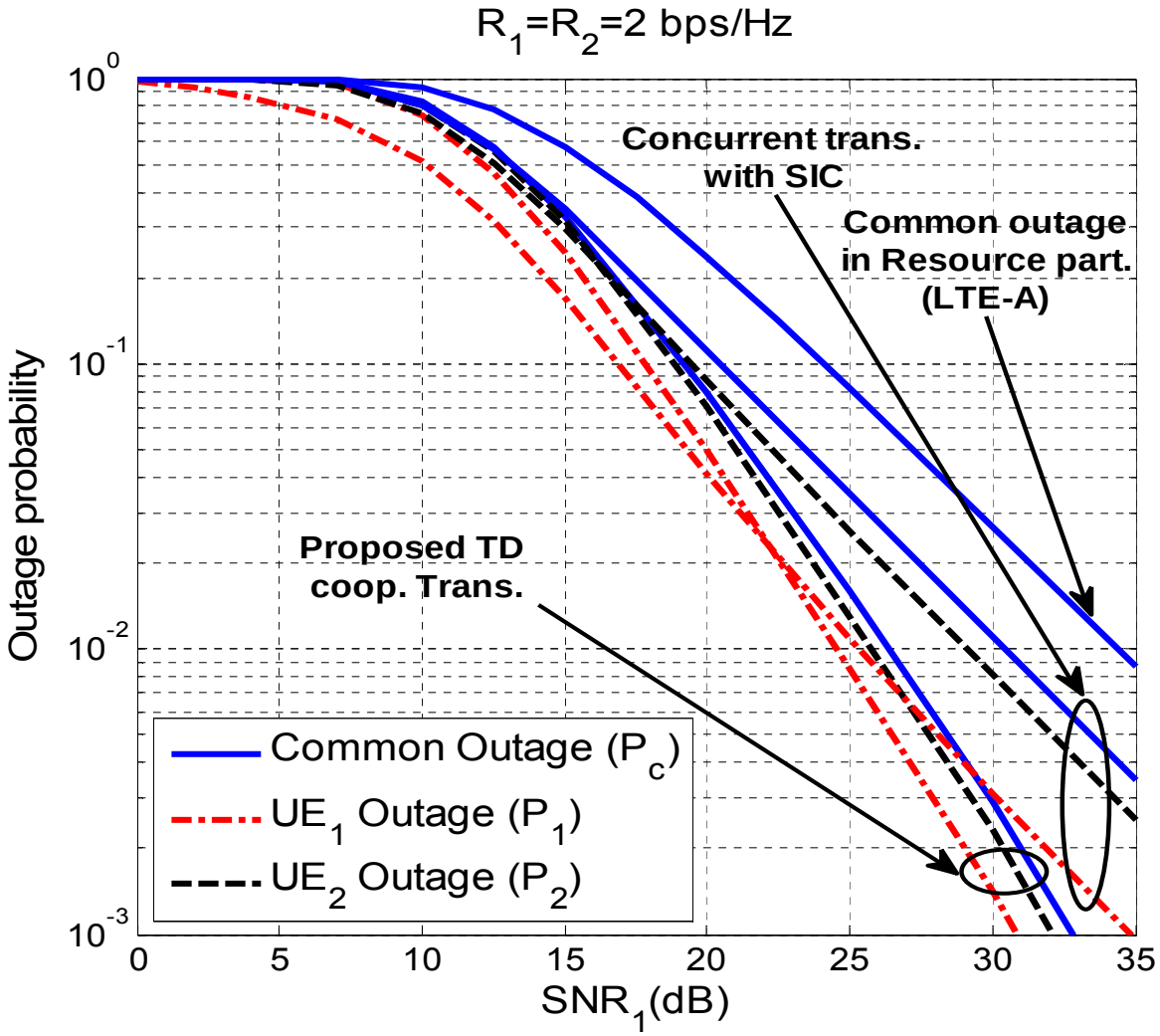
# Outage Probability of User-assisted Relaying

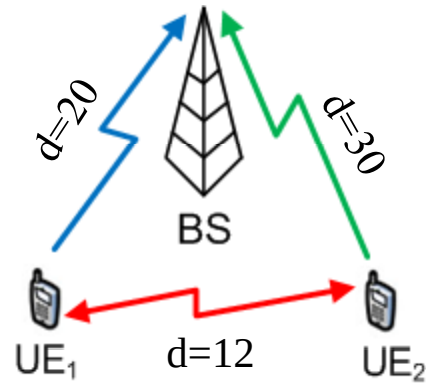


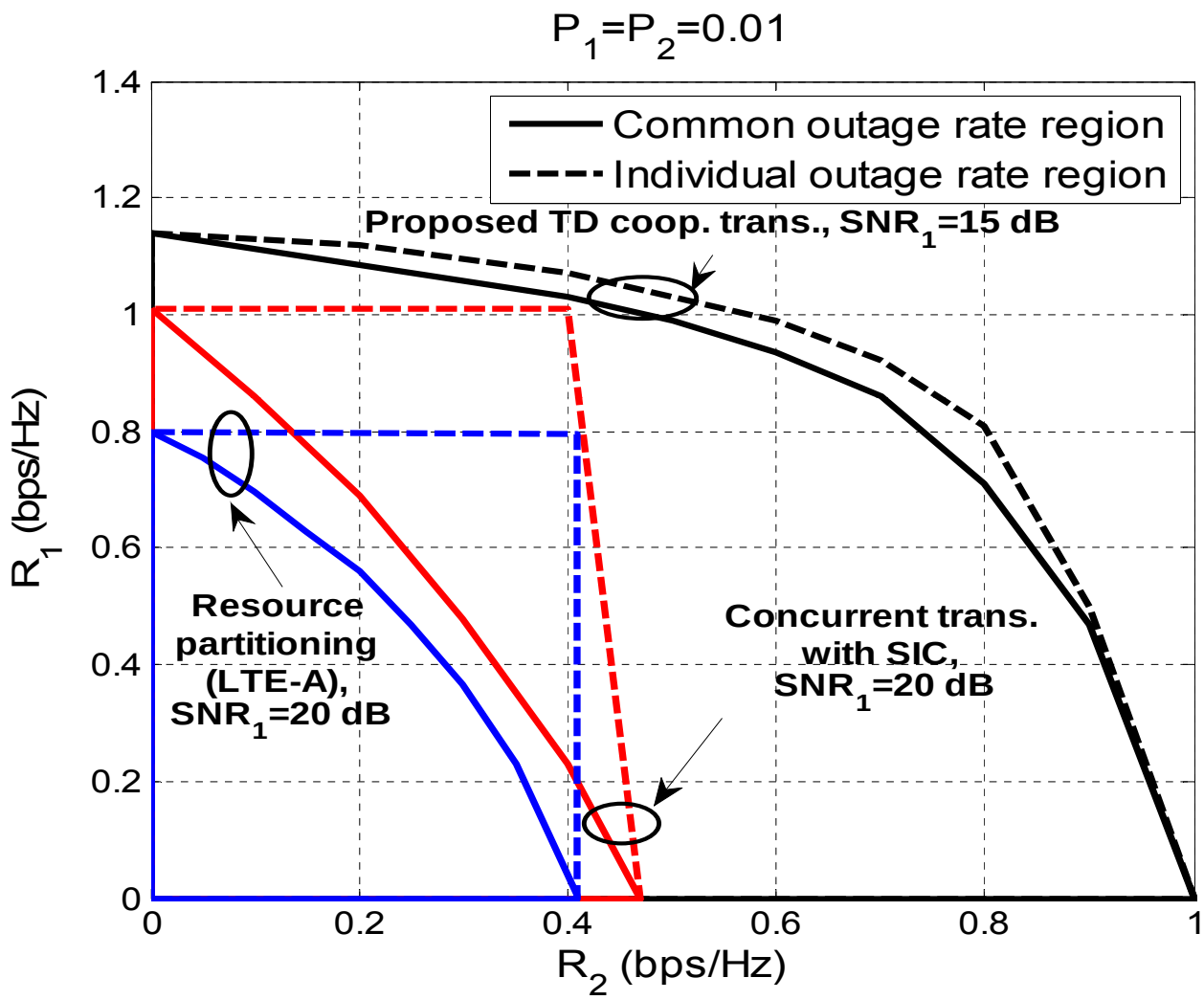

A. Abu Al Haija and M. Vu, "**Outage Analysis for Half-Duplex Partial Decode-Forward Relaying over Fading Channel**," IEEE Globecom, Dec 2014.

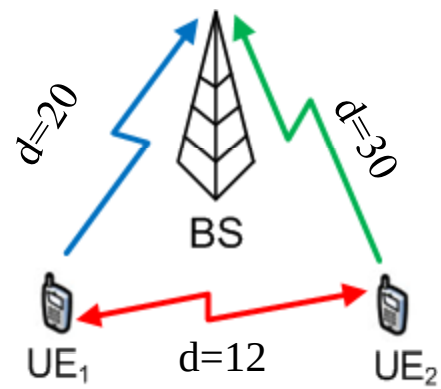
# Outage Probabilities of Both Users Cooperating



# Outage Rate Regions at 1% Outage Probability




A.A.Al Haija and M. Vu, "**Spectral Efficiency and Outage Performance for Hybrid D2D-Infrastructure Uplink Cooperation**," under review IEEE Trans. on Wireless Comm.

# Conclusion

- User-assisted cooperative relaying for uplink communication
  - Utilizes hybrid D2D-infrastructure cooperation
  - Has advanced signal design and decoding
  - Employs partial decode-forward relaying and joint decoding at BS

- Cooperation improves **both** the data rate and reliability
  - Compared to current LTE implementation

- Network deployment shows significant performance gain
  - Average rate gain up to 50%, max gain up to 200%
  - Suitable for crowded metropolitan areas and small cells

# Relevant Publications


- A. Abu Al Haija and M. Vu, “Outage Analysis for Half-Duplex Partial Decode-Forward Relaying over Fading Channel,” IEEE Conf. on Global Comm. (Globecom), Dec. 2014.
- H. ElKotby and M. Vu, “Interference and Throughput Analysis of Uplink User-Assisted Relaying in Cellular Networks,” IEEE 25th Int'l Symp. on Personal, Indoor and Mobile Radio Commun. (PIMRC), Washington DC, Sep 2014.
- A. Abu Al Haija and M. Vu, “Spectral Efficiency and Outage Performance for Hybrid D2D-Infrastructure Uplink Cooperation,” submitted to IEEE Trans. on Wireless Comm., Mar 2014.
- H. ElKotby and M. Vu, “Uplink User-Assisted Relaying Deployment in Cellular Networks,”, submitted to IEEE Trans. on Wireless Comm., Aug. 2014.
- A. Abu Al Haija and M. Vu, “Outage Analysis for Coherent Decode-Forward Relaying over Rayleigh Fading Channels,” submitted to IEEE Trans. on Comm., Aug. 2014.
- A. Abu Al Haija and M. Vu, "Rate Maximization for Half-Duplex Multiple Access with Cooperating Transmitters" IEEE Trans. Comm., vol. 61, no. 9, pp.3620-3634, Sept . 2013.
- A. Abu Al Haija and M. Vu, “Outage Analysis for Uplink Mobile-to-Mobile Cooperation,” IEEE Conf. on Global Comm. (Globecom), Dec 2013.
- A. Abu Al Haija and M. Vu, "Throughput-Optimal Half-Duplex Cooperative Scheme with Partial Decode-Forward Relaying" IEEE ICC, June 2011.
- A. Abu Al Haija and M. Vu, "A Half-Duplex Cooperative Scheme with Partial Decode-Forward Relaying" IEEE ISIT, July 2011.

# More information

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