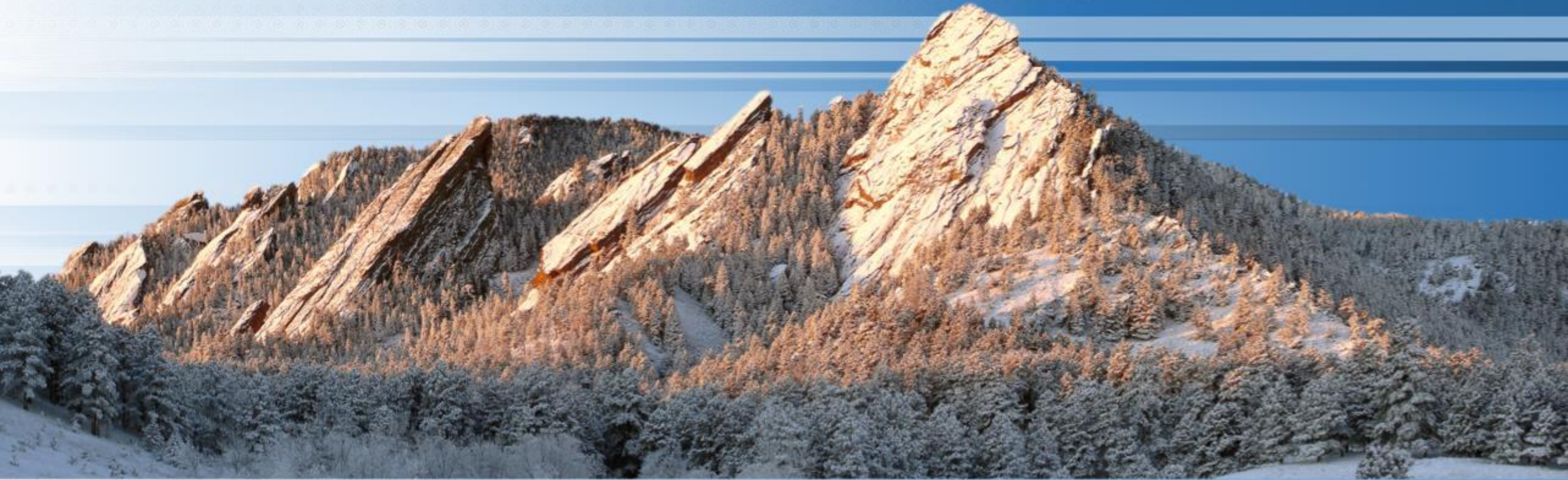


Modeling Device-to-Device Communications for Wireless Public Safety Networks

David Griffith, National Institute of Standards & Technology

Workshop on 5G Technologies for Tactical and First Responder Networks: 23 October 2018

Communications Technology Laboratory (CTL)

Established in 2014

Through development of appropriate measurements and standards:

- Enable robust, mission-critical, interoperable **public safety communications**
- Enable effective and efficient **spectrum use and sharing**
- Enable **advanced communications technologies**
  - Identify **next generation wireless technology measurement challenges**, and develop appropriate measurement science to support innovation.
  - Develop measurements to support **future generations of wireless**: massive-MIMO, mm wave, and support the development of **future generation wireless standards** and pre-standards activities.

Public Safety Communications Research (PSCR) Division

RF Technologies Division

Wireless Networks Division

NIST Boulder

NIST Gaithersburg

Programmatic Areas

Research in Technology, Measurements, and Standards

Spectrum Sharing

3.5 GHz CBRS Band
Test Methods
Requirements
CBRS Tools

5G & Beyond

Millimeter-wave
Channel Measurement & Modeling
Beamforming and Resource Allocation

Public Safety Communications

Device to Device (D2D) Communications
Mission-Critical Push-to-Talk (MCPTT)
Quality of Service (QoS) Priority and Preemption (QPP)

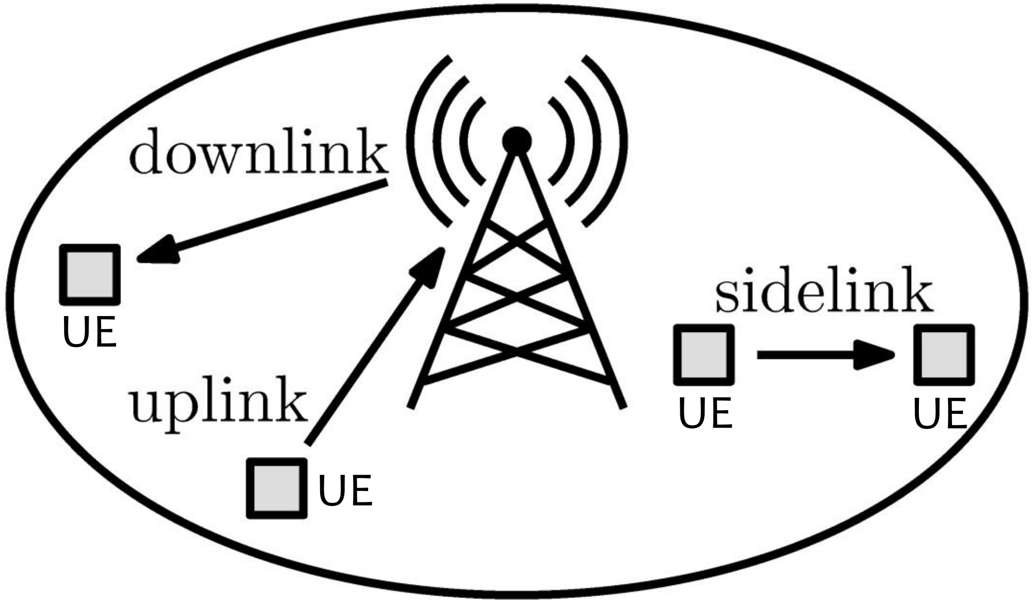
D2D Communications for Public Safety

- First Responders have to communicate in challenging environments where the network infrastructure may be down or non-existent: "out-of-coverage scenario"
- The ability to have device to device (D2D*) communication when in "out-of-coverage" from cellular towers can be the difference between life and death

Sources:
https://media.defense.gov/2012/Jun/29/2000137943/-1/-1/0/120627-F-TQ740-256.JPG
https://www.dhs.gov/science-and-technology/wildland-fire-fighter-uniform-redesigned
http://wirelessestimator.com/content/articles/?pagename=Cell%20Site%20Tower%20News

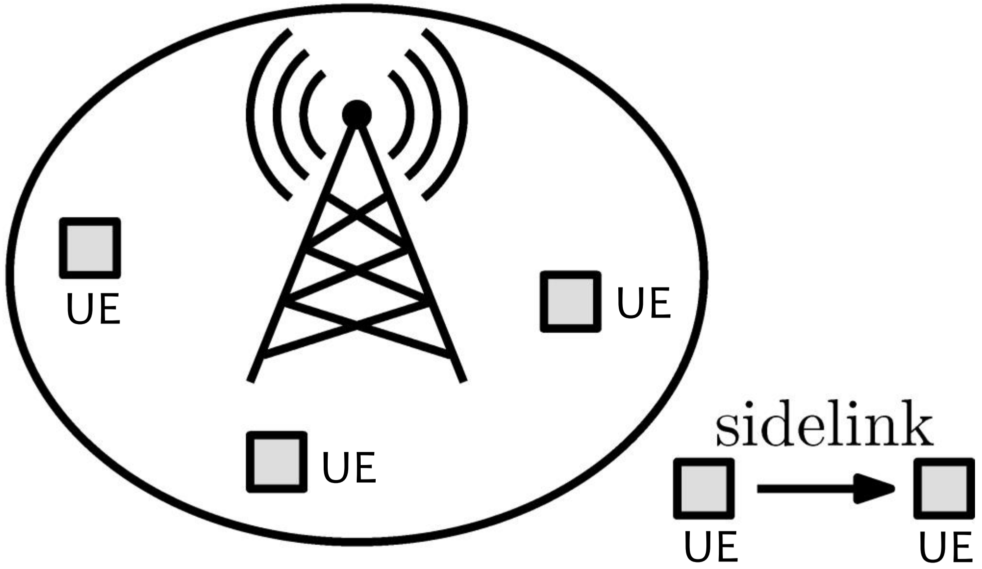
In-Coverage vs. Out-of-Coverage D2D Communications

In-Coverage



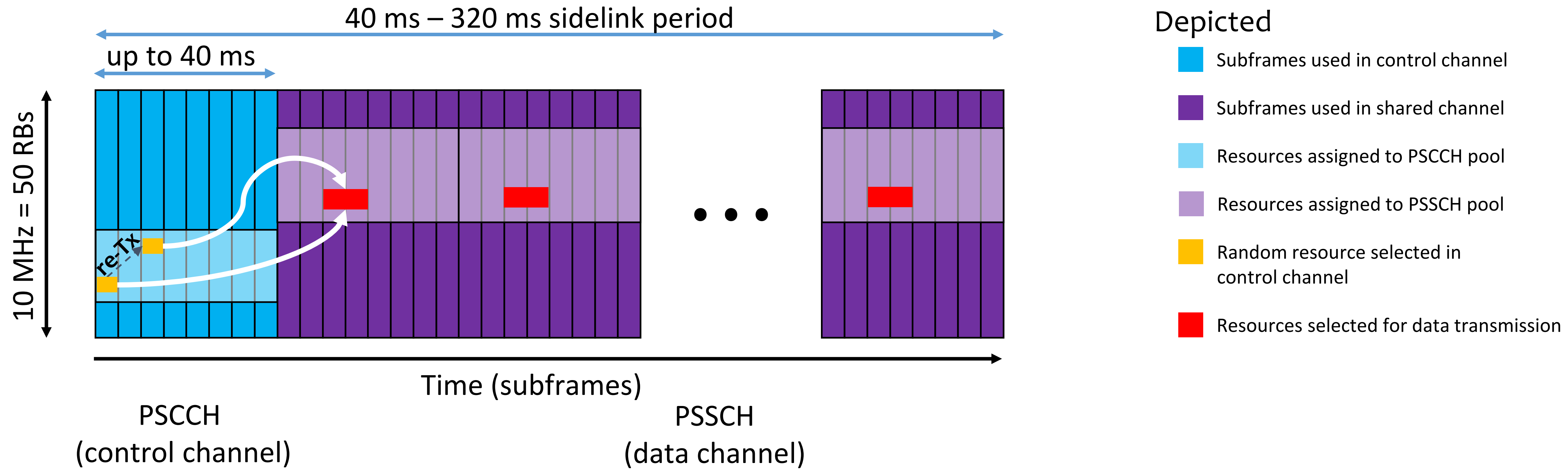
- D2D Communications can be coordinated by base station
- Allows offloading of intra-cell traffic, lower latency

Out-of-Coverage (OOC)



- No base station control of D2D communications
- Allows communications with degraded/destroyed/absent infrastructure

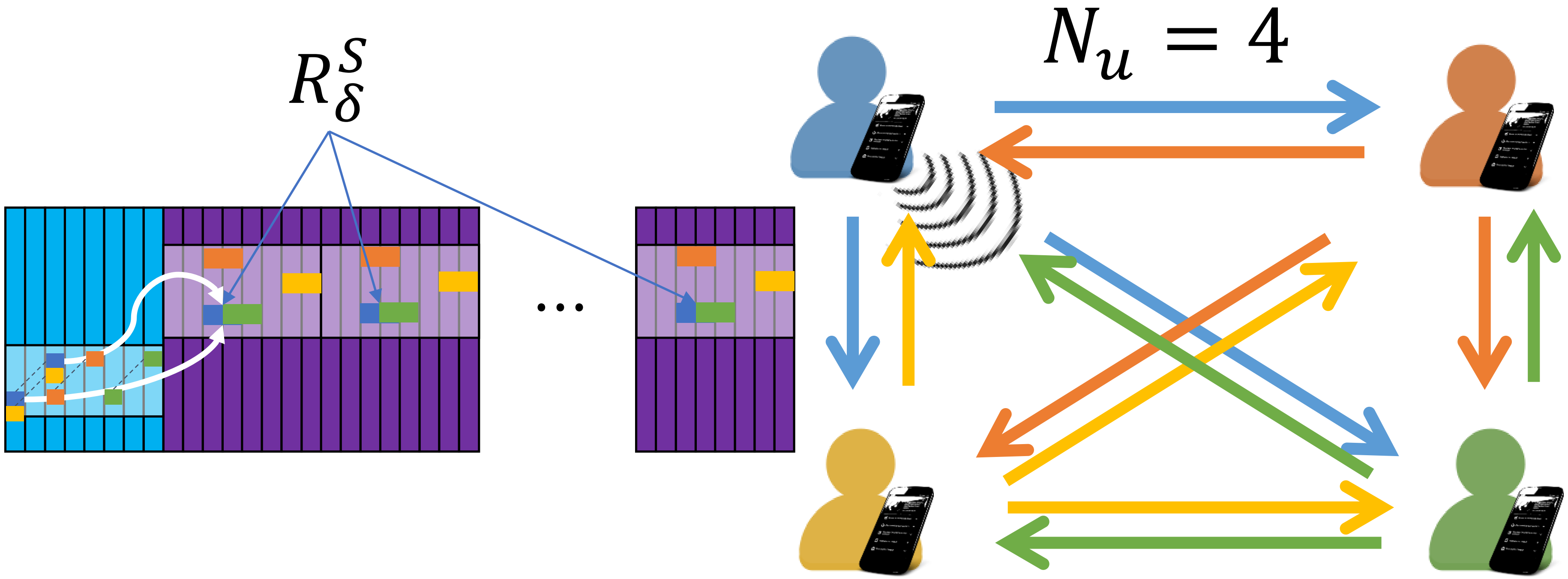
The Physical Sidelink Control and Shared Channels



- **Transmitting UEs:** To transmit, an OOC UE selects a **random resource** in the PSCCH pool to send a Sidelink Control Information (SCI) Message, indicating where and how the data will be transmitted.
- **Listening UEs:** Each UE listens to the control channel to learn whether other UEs are going to transmit and what resources they will use

D2D Communications Performance Modeling

- Given a group of N_u OOC **half-duplex** UEs communicating using D2D:
  - **What is the probability of event R_δ^S: δ UEs receive and decode a transmitted block of data on the Shared Channel (PSSCH) from a random UE in the group?**



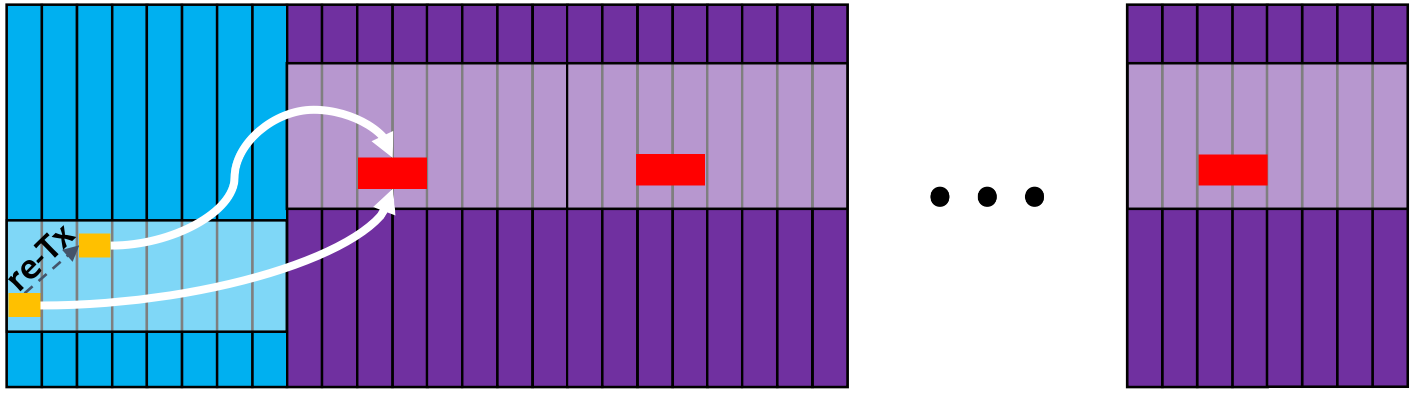
$\Pr\{R_0^S\} = ?$

$\Pr\{R_1^S\} = ?$

$\Pr\{R_2^S\} = ?$

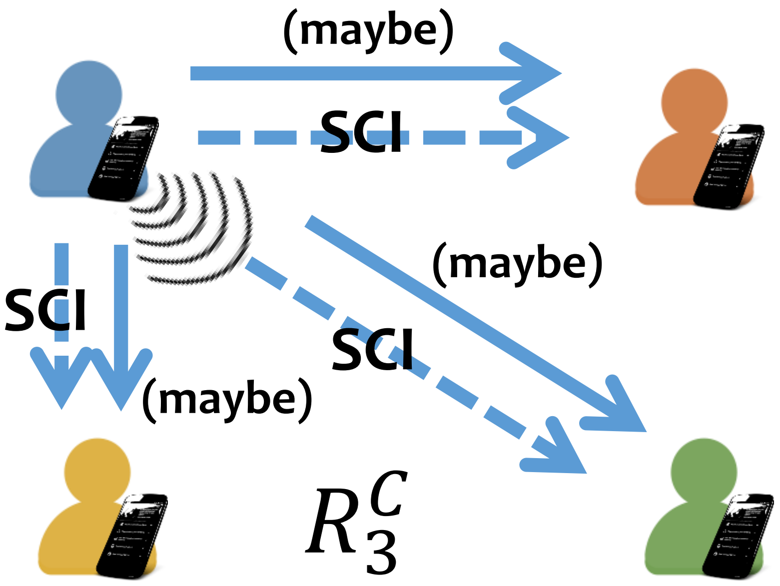
$\Pr\{R_3^S\} = ?$

SCI Message Decode Failure = “No Data for You” ☹



PSCCH
(control channel)

PSSCH
(data channel)



$$\Pr\{R_\delta^S\} = \sum_{\rho=0}^{N_u-1} \Pr\{R_\delta^S \mid R_\rho^C\} \Pr\{R_\rho^C\}$$

Event R_ρ^C: ρ UEs receive UE_0’s SCI message

D. Griffith, F. Cintron, and R. Rouil, “Physical Sidelink Control Channel (PSCCH) in Mode 2: Performance Analysis,” ICC 2017, Paris, France, May 2017.

D. Griffith, F. Cintrón, A. Galazka, T. Hall, and R. Rouil, “Performance of the Physical Sidelink Shared Channel (PSSCH) for Out-of-Coverage Communications,” ICC 2018, Kansas City, MO, May 2018.

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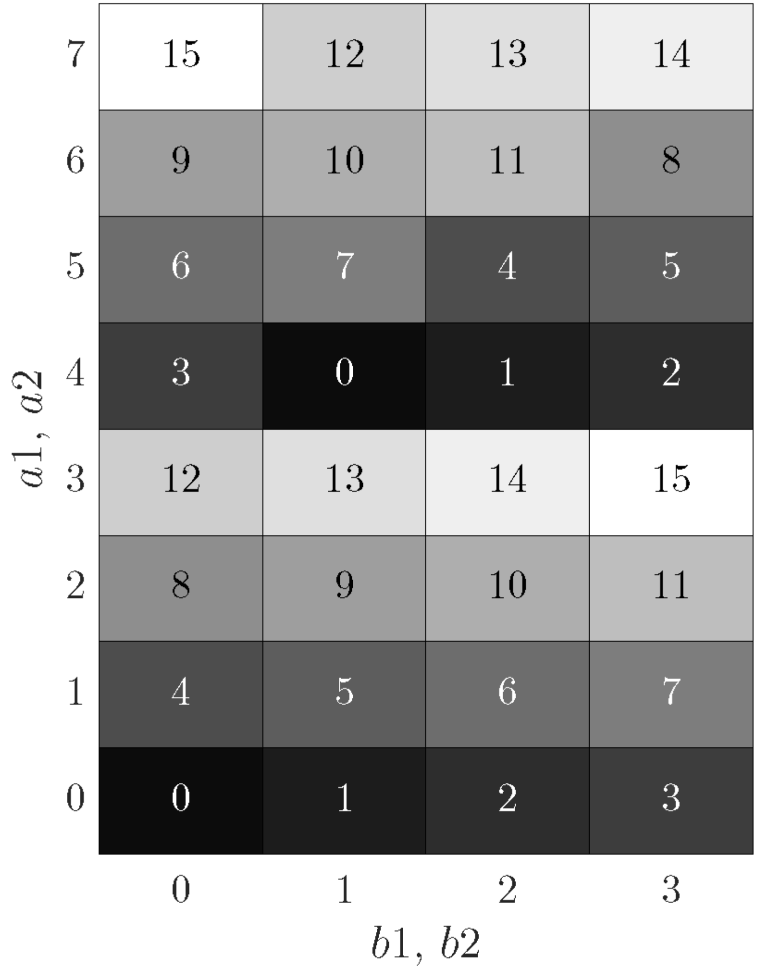
Control Channel Resource Mapping

- OOC UEs that are pick control channel resources for SCI messages (2 per msg)
- Each resource index maps to 2 ordered pairs (a_1, b_1) and (a_2, b_2) that ID two unique locations in the resource pool
- The example grid shows a 16-resource pool consisting of 32 Resource Blocks



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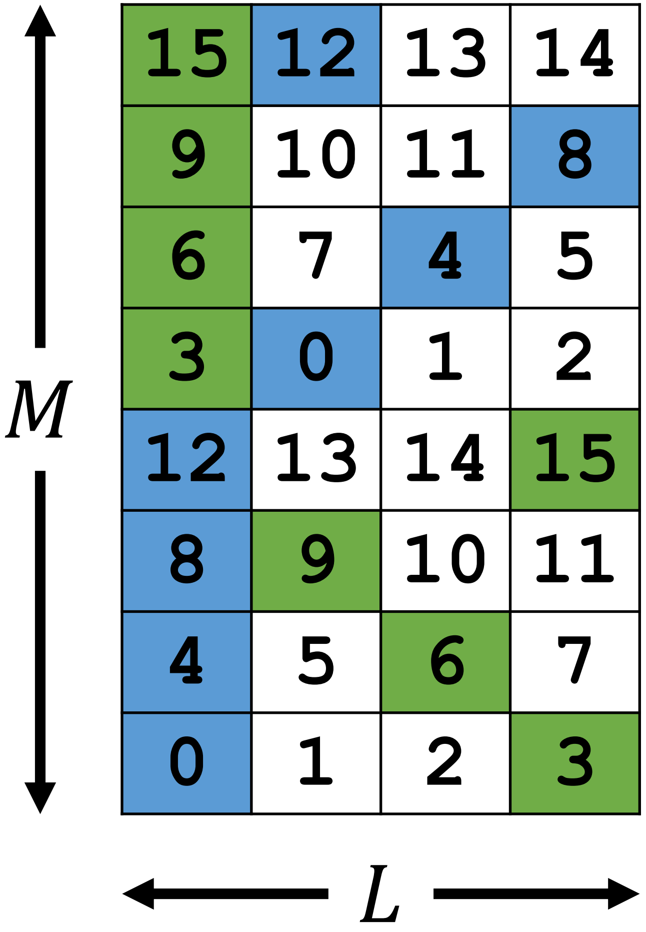
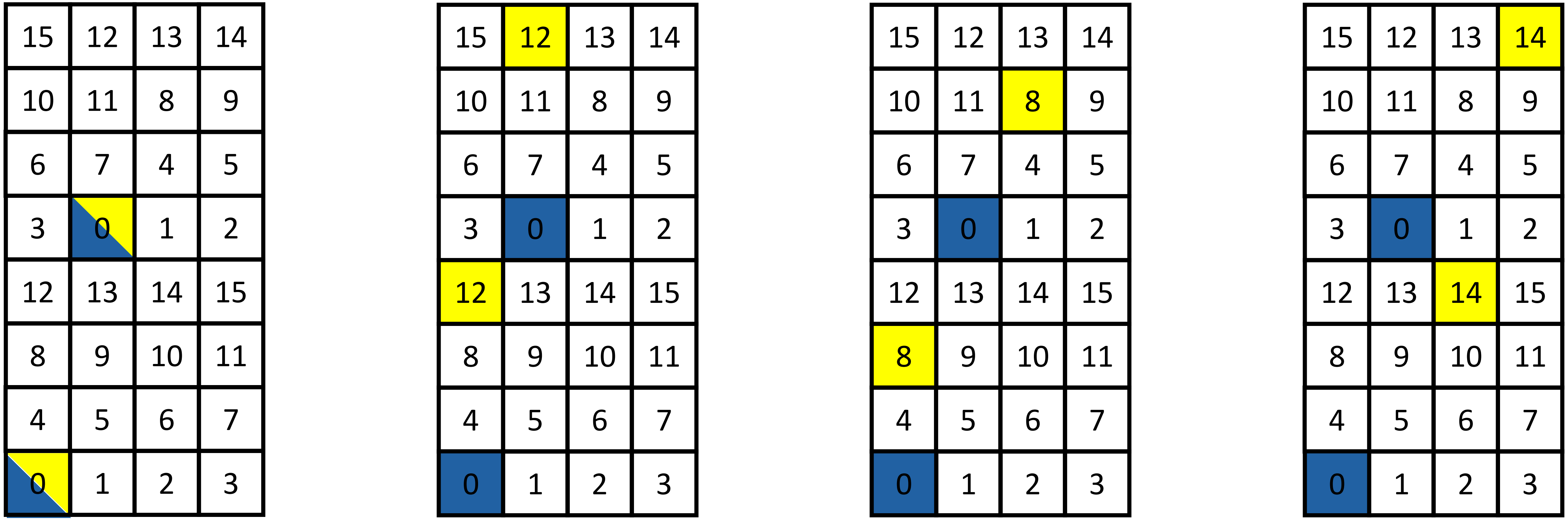
Pool Dimensional Parameters



- L: width in subframes; M: height in resource blocks
- Number of resources: $N = LM/2$
- Divide $M/2$ by $(L - 1)$:
  - Number of complete diagonals: $q = \left\lfloor \left(\frac{M}{2}\right) / (L - 1) \right\rfloor$
  - Resources in partial diagonal: $r = \frac{M}{2} \bmod (L - 1)$
- In this example:
  - $L = 4, M = 8$
  - $N = \frac{4 \times 8}{2} = 16$
  - $q = \lfloor 4/3 \rfloor = 1$
  - $r = 4 \bmod 3 = 1$

Collisions and Overlaps (2 UEs)



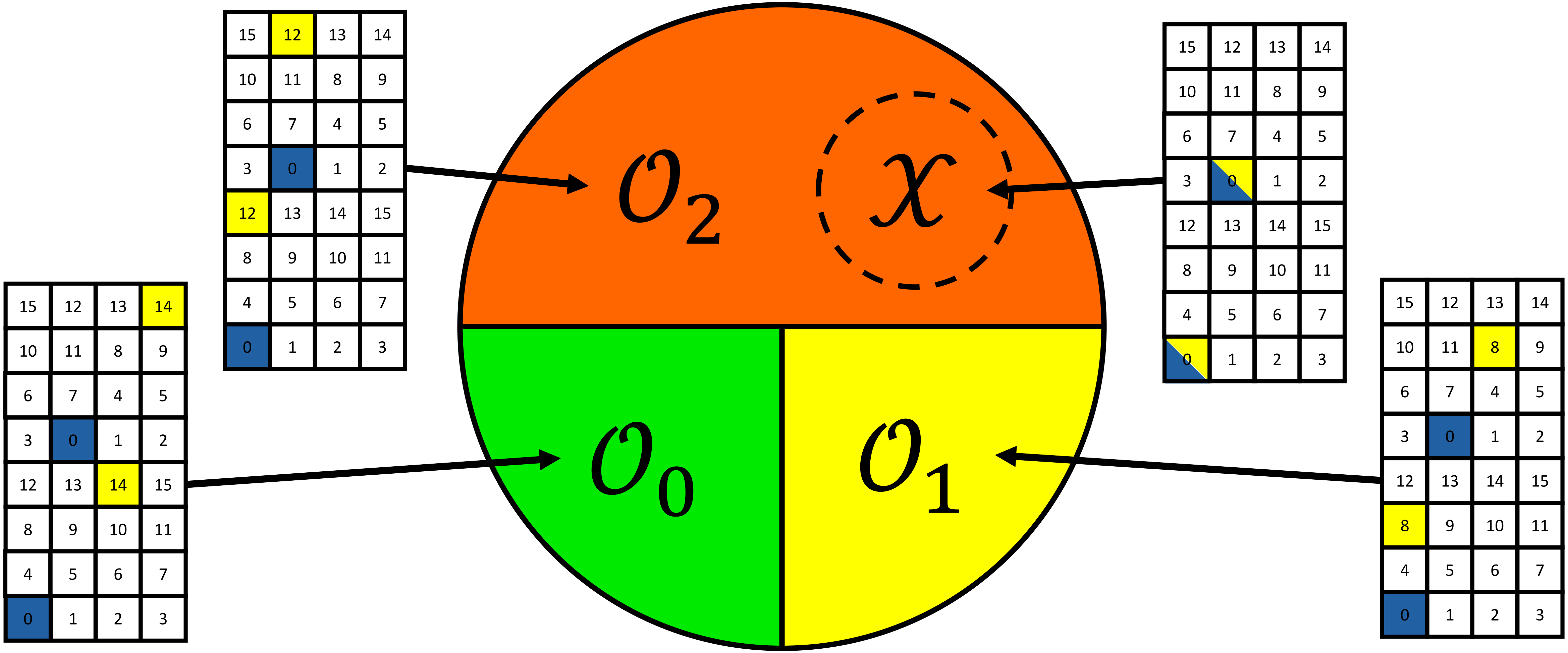
Collision ($\mathcal{X}$): Two UEs pick the same resource; both message copies are lost.

Double Overlap ($\mathcal{O}_2$): Two UEs pick different resources but transmit in the same pair of subframes.

Single Overlap ($\mathcal{O}_1$): Two UEs pick different resources and overlap in one subframe.

No Overlap ($\mathcal{O}_0$): Two UEs pick different resources, with no subframe overlap.

Venn Diagram of Subframe Overlap Outcomes



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Two Cases to Consider:

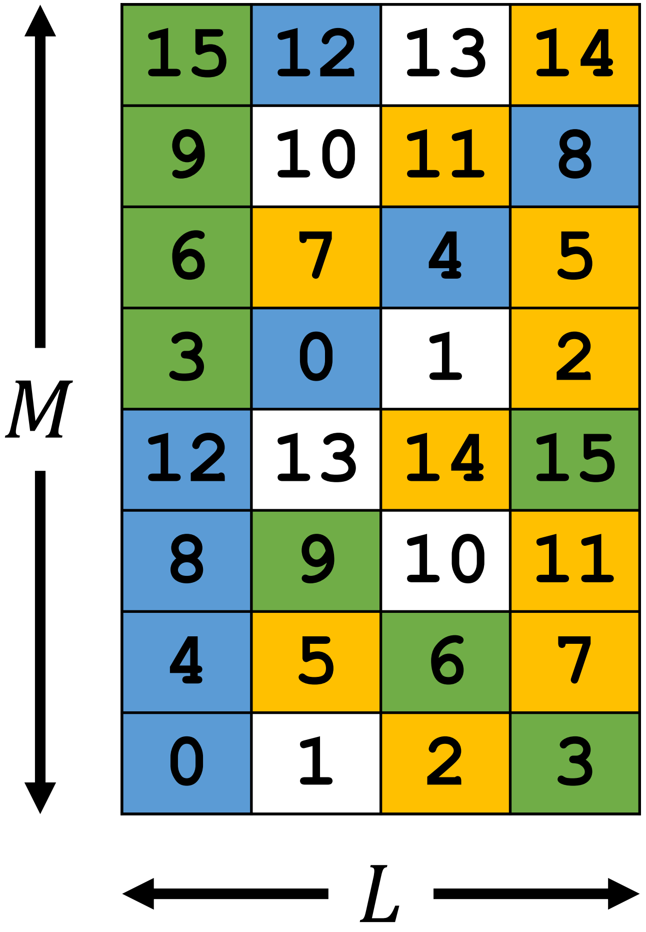
- $0 \leq r \leq \lfloor (L-1)/2 \rfloor$
  - Partial diagonals don't overlap
  - Ex: $q = 1, r = 1$

15	12	13	14
9	10	11	8
6	7	4	5
3	0	1	2
12	13	14	15
8	9	10	11
4	5	6	7
0	1	2	3

- $\lfloor (L-1)/2 \rfloor < r < L-1$
  - Partial diagonals overlap
  - Ex: $q = 1, r = 2$

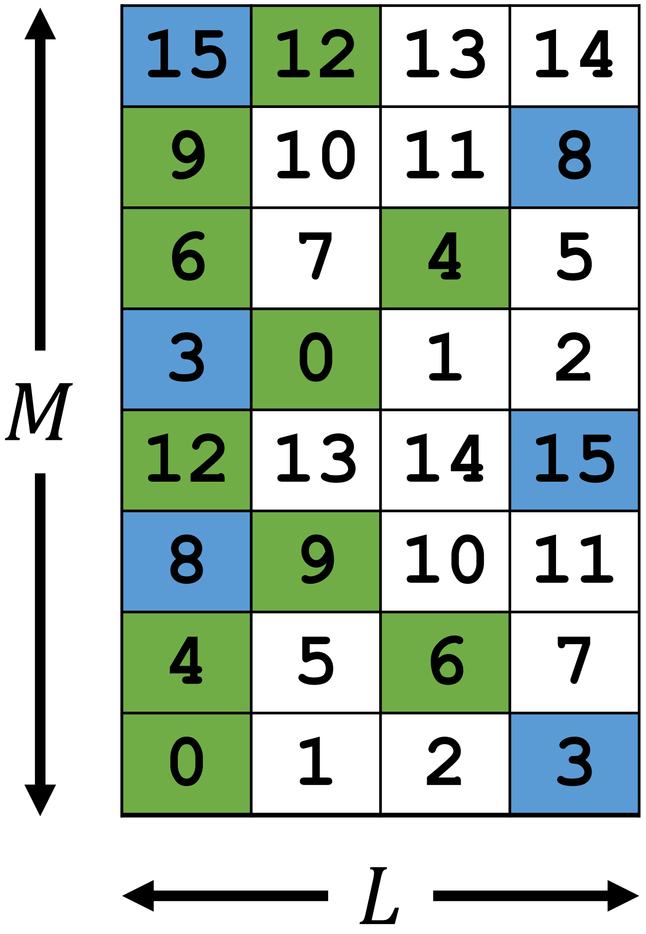
18	19	16	17
15	12	13	14
9	10	11	8
6	7	4	5
3	0	1	2
16	17	18	19
12	13	14	15
8	9	10	11
4	5	6	7
0	1	2	3

Probability of No Overlaps ($\Pr\{\mathcal{O}_0\}$)



- If one UE picks a resource in the 1st column whose 2nd copy is in the 2nd column, then there are 3 out of 16 possible resources for the other UE to choose
- If one UE picks a resource in the 1st column whose 2nd copy is in the 3nd column, then there are 2 out of 16 possible resources for the other UE to choose
- If one UE picks a resource in the 1st column whose 2nd copy is in the 4nd column, then there are 3 out of 16 possible resources for the other UE to choose
- Thus $\Pr\{\mathcal{O}_0\} = \frac{3}{8} \times \frac{3}{16} + \frac{2}{8} \times \frac{2}{16} + \frac{3}{8} \times \frac{3}{16} = \frac{11}{64}$

Probability of One Overlap ($\Pr\{\mathcal{O}_1\}$)



- If one UE picks a resource in the 1st column whose 2nd copy is in the 2nd column, then there are 5 out of 8 possible resources for the other UE to choose
- If one UE picks a resource in the 1st column whose 2nd copy is in the 3nd column, then there are 6 out of 8 possible resources for the other UE to choose
- If one UE picks a resource in the 1st column whose 2nd copy is in the 4nd column, then there are 5 out of 8 possible resources for the other UE to choose
- Thus $\Pr\{\mathcal{O}_1\} = \frac{3}{8} \times \frac{5}{8} + \frac{2}{8} \times \frac{6}{8} + \frac{3}{8} \times \frac{5}{8} = \frac{21}{32}$

The probability that ρ UEs Decode the SCI Message

$N_u = 4$

Control Channel Resources (12)

Probability of picking 's resource: $\frac{1}{12}$

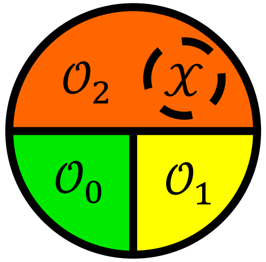
Probability no one picks 's resource: $\left(1 - \frac{1}{12}\right)^3 = \left(\frac{11}{12}\right)^3$

Probability at least one of picks 's resource and no one gets 's SCI message: $1 - \left(\frac{11}{12}\right)^3$

If no one lands on 's resource: event R_ρ^C happens if:

ρ out of $(N_u - 1)$ UEs experience success, each with probability $\Pr\{\mathcal{O}_0 \cup \mathcal{O}_1\} = \Pr\{\mathcal{O}_0\} + \Pr\{\mathcal{O}_1\}$

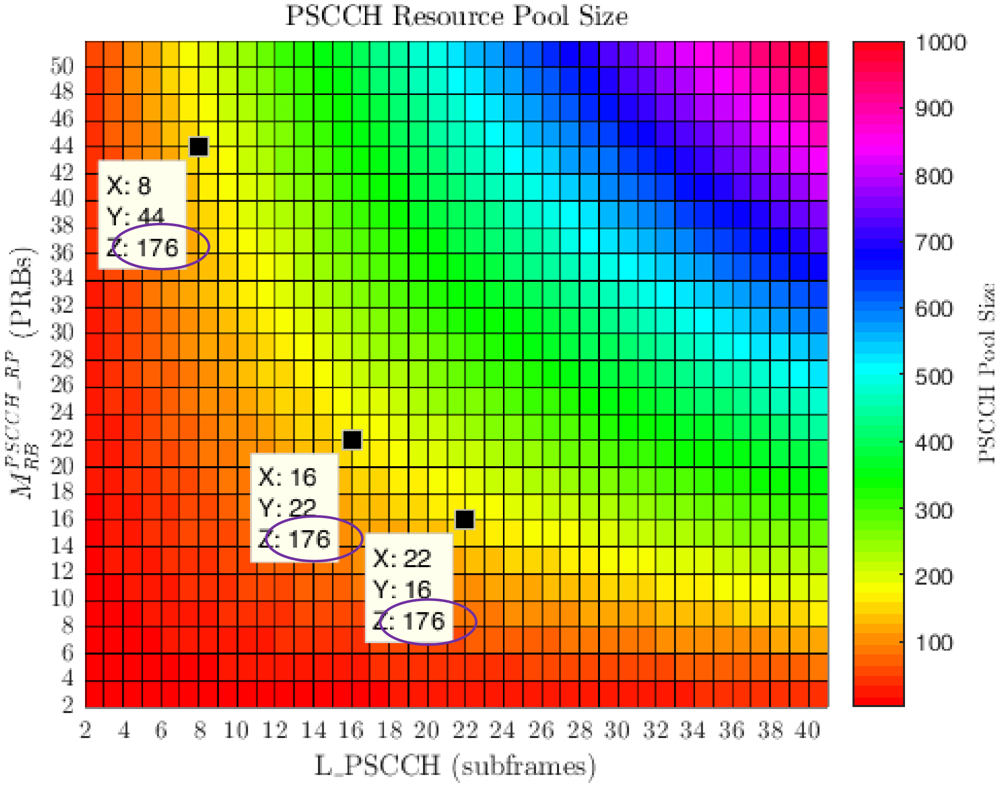
$(N_u - \rho - 1)$ UEs experience failure, each with probability $\Pr\{\mathcal{O}_2 \cap \bar{X}\}$

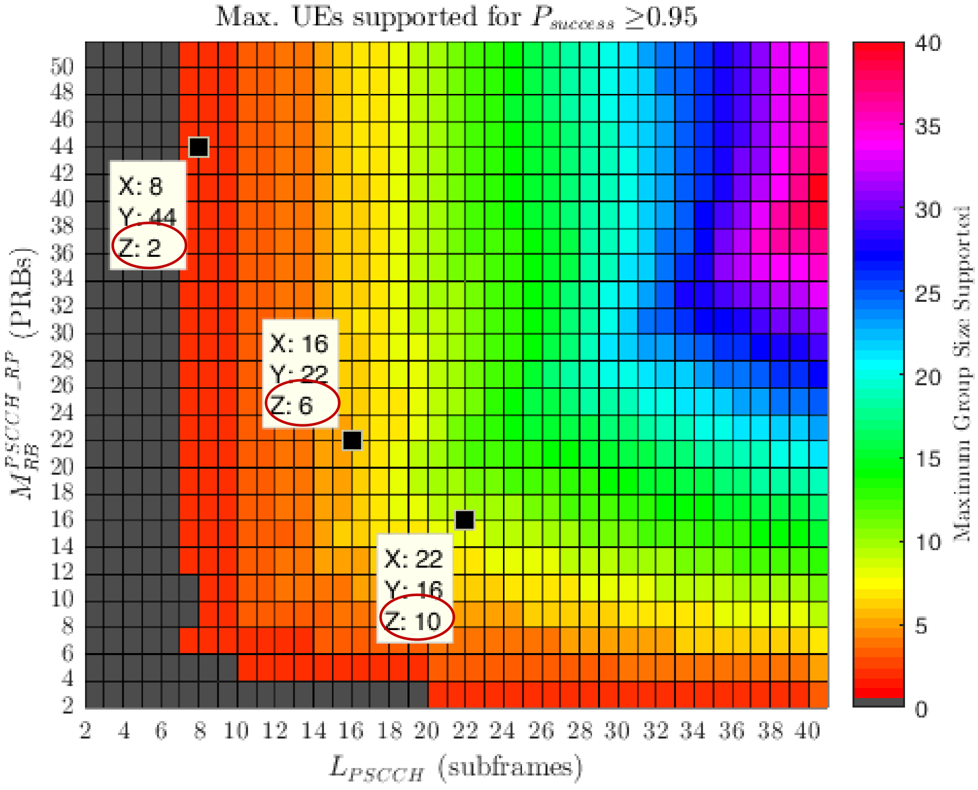


Probability of s successes out of t independent trials is $\binom{t}{s} \Pr\{\text{success}\}^s \, (1 - \Pr\{\text{success}\})^{t-s}$

$$\Pr\{R_\rho^C\} = \left[1 - \left(1 - \frac{1}{N}\right)^{N_u - 1}\right] \delta[\rho] + \binom{N_u - 1}{\rho} (\Pr\{\mathcal{O}_0\} + \Pr\{\mathcal{O}_1\})^\rho (\Pr\{\mathcal{O}_2 \cap \bar{X}\})^{N_u - \rho - 1}$$

Effect of PSCCH Dimensions on Performance





- We look at three configurations producing a pool of 176 resources (Z value on left graph)
  - The maximum number of UEs supported (Z value on right graph) is different due to the constraints associated with half duplex transmissions

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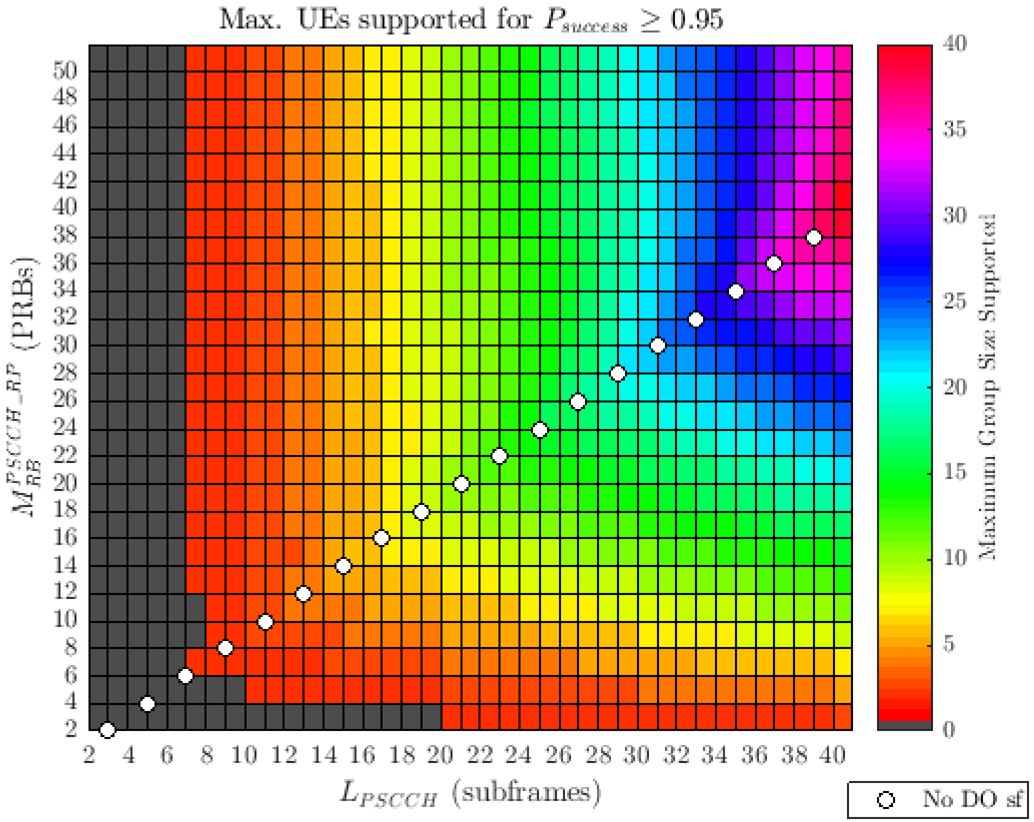
Optimizing the PSCCH

- Pool configurations with no double overlaps (aside collisions) are able to support more UEs than other pools having comparable number of resources.
  - *The number of PRBs should be less than the number of subframes*, and
  - *We get the best performance when the number of PRBs is one less than the number of subframes*



32	33	34	35	27	28	29	30	31
24	25	26	18	19	20	21	22	23
16	17	9	10	11	12	13	14	15
8	0	1	2	3	4	5	6	7
27	28	29	30	31	32	33	34	35
18	19	20	21	22	23	24	25	26
9	10	11	12	13	14	15	16	17
0	1	2	3	4	5	6	7	8

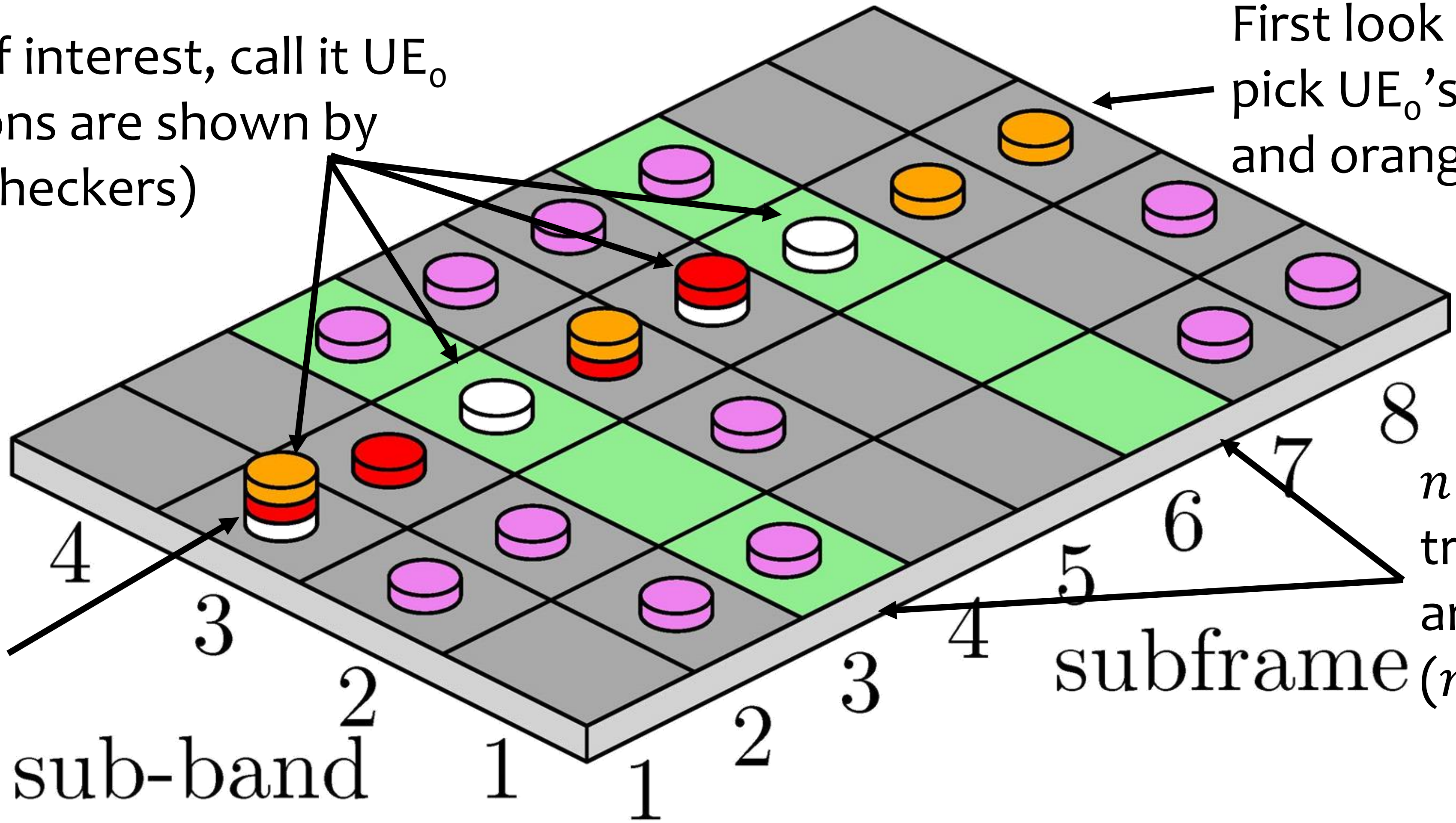
Shared Channel Subframes and TRP Masks

Pick a UE of interest, call it UE_0 (its selections are shown by the white checkers)

First look at the UEs that pick UE_0's sub-band (red and orange checkers)

Each UE independently picks its mask, so collisions can happen

n out of UE_0's transmissions are not collided ($n = 2$ here)



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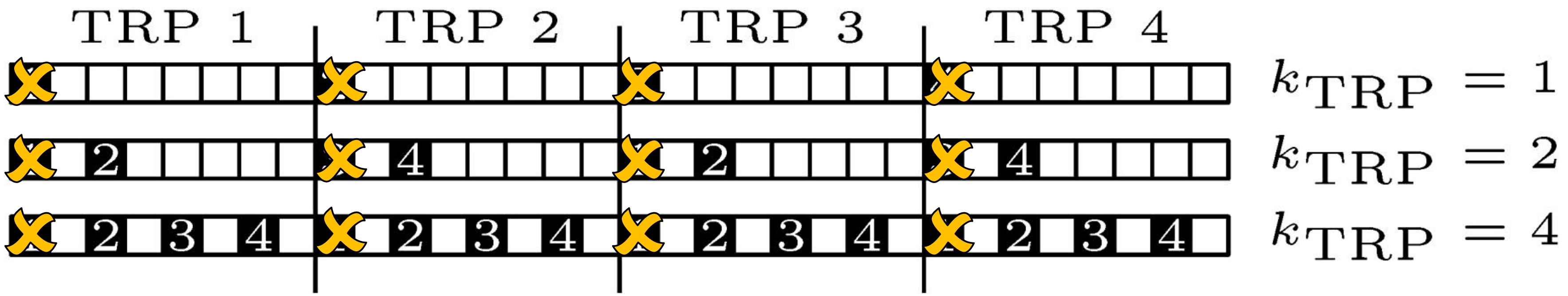
Modeling the PSSCH's HARQ Function



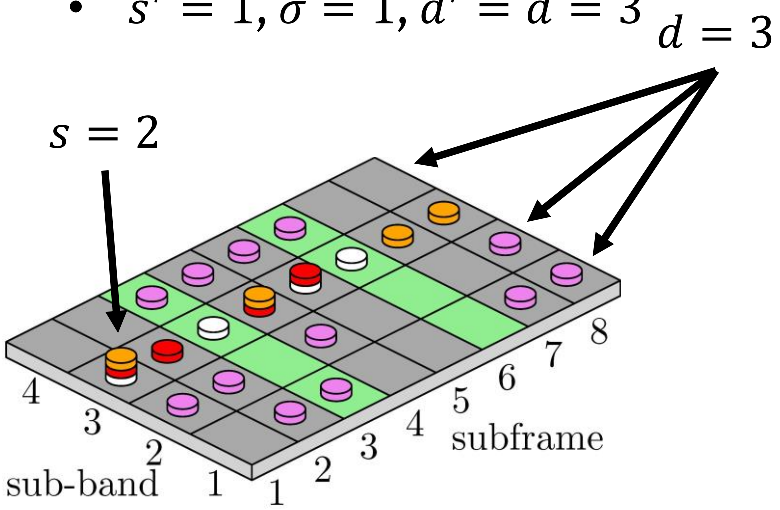
n	k_{TRP}		
	1	2	4
0	ψ_0	ψ_0	ψ_0
1	ψ_4	ψ_2	ψ_1
2	–	ψ_4	ψ_2
3	–	–	ψ_3
4	–	–	ψ_4

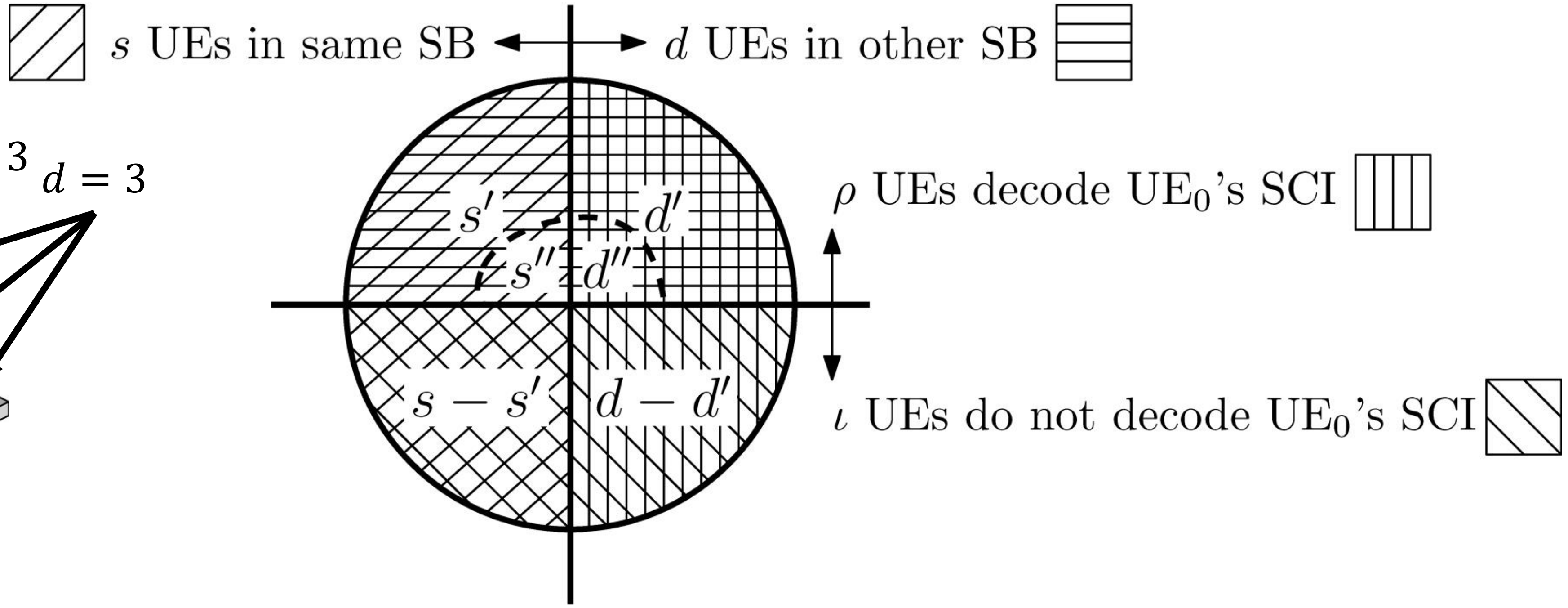
- A UE uses the same *subframe mask* for each TRP in that period
  - At the start of each period, the UE picks a fresh mask
- Every Shared Channel transmission uses 4 HARQ Redundant Versions (RVs)
  - HARQ is done without feedback, so 4 RVs go out no matter what
- Define $\boldsymbol{\psi_i = Pr\{\text{UE decodes message given it received } i \text{ RVs out of } 4\}}$
- Collisions have different effects, depending on k_{TRP}

Categorizing UEs Using Control Channel Events

- There are $(N_u - 1)$ UEs in the group; we partition them in 2 ways:
  - Did the UE receive UE_0's SCI? (ρ did, and ι didn't)
  - Did the UE pick the same sub-band as UE_0? (s did, and d didn't)
  - (To save space, we define $\sigma = s - s'$ in our analysis)

- Red and purple decoded SCI:
  - $s' = 1, \sigma = 1, d' = d = 3$





The Conditional Distribution

$$\Pr\{\mathcal{R}_\delta^S \,|\, \mathcal{R}_\rho^C\} = \sum_{s'=0}^{\rho} \sum_{\sigma=0}^{\iota} \binom{\rho}{s'}\binom{\iota}{\sigma} \left(\frac{1}{N_{\mathrm{sb}}}\right)^{s'+\sigma} \left(1 - \frac{1}{N_{\mathrm{sb}}}\right)^{(N_u-1)-(s'+\sigma)}$$
$$\times \left(\sum_{n=0}^{k_{\mathrm{TRP}}} \left[\sum_{\ell=n}^{k_{\mathrm{TRP}}} (-1)^{\ell-n} \binom{\ell}{n} \binom{k_{\mathrm{TRP}}}{\ell} \left[\binom{N_{\mathrm{TRP}}-\ell}{k_{\mathrm{TRP}}} / \binom{N_{\mathrm{TRP}}}{k_{\mathrm{TRP}}} \right]^{s'+\sigma} \right] \right.$$
$$\left. \times \left[\sum_{s''=\max(0,s'-\rho+\delta)}^{\min(\delta,s')} \binom{s'}{s''} \omega_n^{s''} (1-\omega_n)^{s'-s''} \binom{\rho-s'}{\delta-s''} \phi_n^{\delta-s''} (1-\phi_n)^{(\rho-s')-(\delta-s'')} \right] \right)$$

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First conditioning: UE$_0$'s Sub-Band

Pr{s' receivers and σ interferers pick UE-of-interest's sub-band}

$$\Pr\{\mathcal{R}_\delta^S \mid \mathcal{R}_\rho^C\} = \sum_{s'=0}^{\rho}\sum_{\sigma=0}^{\iota} \binom{\rho}{s'}\binom{\iota}{\sigma}\left(\frac{1}{N_{\text{sb}}}\right)^{s'+\sigma}\left(1-\frac{1}{N_{\text{sb}}}\right)^{(N_u-1)-(s'+\sigma)}$$

$$\times\left(\sum_{n=0}^{k_{\text{TRP}}}\left[\sum_{\ell=n}^{k_{\text{TRP}}}(-1)^{\ell-n}\binom{\ell}{n}\binom{k_{\text{TRP}}}{\ell}\left[\binom{N_{\text{TRP}}-\ell}{k_{\text{TRP}}}\Big/\binom{N_{\text{TRP}}}{k_{\text{TRP}}}\right]^{s'+\sigma}\right]\right.$$

$$\left.\times\left[\sum_{s''=\max(0,s'-\rho+\delta)}^{\min(\delta,s')}\binom{s'}{s''}\omega_n^{s''}(1-\omega_n)^{s'-s''}\binom{\rho-s'}{\delta-s''}\phi_n^{\delta-s''}(1-\phi_n)^{(\rho-s')-(\delta-s'')}\right]\right)$$

Pr{$\mathcal{R}_\delta^S \mid \mathcal{R}_\rho^C \cap$ "s' receivers and σ interferers pick UE-of-interest's sub-band"}

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Second conditioning: Number of Non-Collided Subframes

Pr$\{s'$ receivers and σ interferers pick UE-of-interest's sub-band$\}$

Pr$\{n$ of the UE-of-interest's k_{TRP} transmissions are not blocked$\}$

$$\Pr\{\mathcal{R}_\delta^S \,|\, \mathcal{R}_\rho^C\} = \sum_{s'=0}^{\rho}\sum_{\sigma=0}^{\iota} \binom{\rho}{s'}\binom{\iota}{\sigma}\left(\frac{1}{N_{\mathrm{sb}}}\right)^{s'+\sigma}\left(1-\frac{1}{N_{\mathrm{sb}}}\right)^{(N_u-1)-(s'+\sigma)}$$

$$\times\left(\sum_{n=0}^{k_{\mathrm{TRP}}}\left[\sum_{\ell=n}^{k_{\mathrm{TRP}}}(-1)^{\ell-n}\binom{\ell}{n}\binom{k_{\mathrm{TRP}}}{\ell}\left[\binom{N_{\mathrm{TRP}}-\ell}{k_{\mathrm{TRP}}}\Big/\binom{N_{\mathrm{TRP}}}{k_{\mathrm{TRP}}}\right]^{s'+\sigma}\right]\right.$$

$$\left.\times\left[\sum_{s''=\max(0,s'-\rho+\delta)}^{\min(\delta,s')}\binom{s'}{s''}\omega_n^{s''}(1-\omega_n)^{s'-s''}\binom{\rho-s'}{\delta-s''}\phi_n^{\delta-s''}(1-\phi_n)^{(\rho-s')-(\delta-s'')}\right]\right)$$

Pr$\{\mathcal{R}_\delta^S \,|\, \mathcal{R}_\rho^C \cap$ "s' receivers and σ interferers pick UE-of-interest's sub-band"
$\cap$ "n of the UE-of-interest's k_{TRP} transmissions are not blocked"$\}$

Pr$\{\mathcal{R}_\delta^S \,|\, \mathcal{R}_\rho^C \cap$ "s' receivers and σ interferers pick UE-of-interest's sub-band"$\}$

Last step: Success probabilities for other-sub-band UEs

Pr{s' receivers and σ interferers pick UE-of-interest's sub-band}

Pr{n of the UE-of-interest's k_{TRP} transmissions are not blocked}

$$\Pr\{\mathcal{R}^S_\delta \mid \mathcal{R}^C_\rho\} = \sum_{s'=0}^{\rho}\sum_{\sigma=0}^{\iota} \binom{\rho}{s'}\binom{\iota}{\sigma}\left(\frac{1}{N_{\mathrm{sb}}}\right)^{s'+\sigma}\left(1-\frac{1}{N_{\mathrm{sb}}}\right)^{(N_u-1)-(s'+\sigma)}$$
$$\times\left(\sum_{n=0}^{k_{\mathrm{TRP}}}\left[\sum_{\ell=n}^{k_{\mathrm{TRP}}}(-1)^{\ell-n}\binom{\ell}{n}\binom{k_{\mathrm{TRP}}}{\ell}\left[\binom{N_{\mathrm{TRP}}-\ell}{k_{\mathrm{TRP}}}\Big/\binom{N_{\mathrm{TRP}}}{k_{\mathrm{TRP}}}\right]^{s'+\sigma}\right]\right.$$
$$\left.\times\left[\sum_{s''=\max(0,s'-\rho+\delta)}^{\min(\delta,s')}\binom{s'}{s''}\omega_n^{s''}(1-\omega_n)^{s'-s''}\binom{\rho-s'}{\delta-s''}\phi_n^{\delta-s''}(1-\phi_n)^{(\rho-s')-(\delta-s'')}\right]\right)$$

Pr{s'' UEs in UE-of-interest's sub-band decode message | ...}

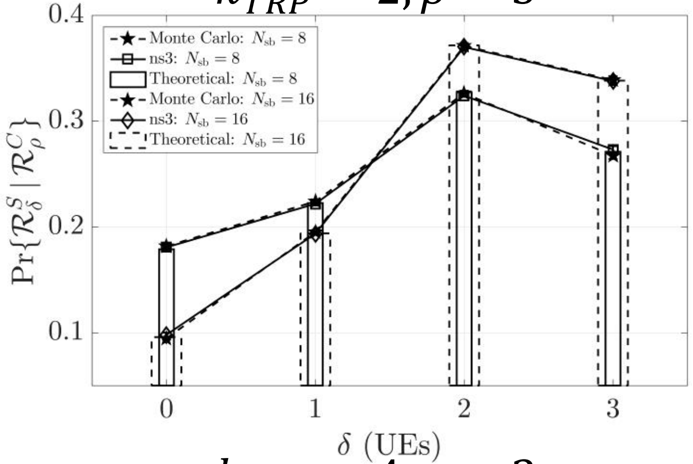
Pr{$d'' = (\delta - s'')$ UEs in other sub-bands decode message | ...}

Pr{$\mathcal{R}^S_\delta \mid \mathcal{R}^C_\rho$ ∩ "s' receivers and σ interferers pick UE-of-interest's sub-band" ∩ "n of the UE-of-interest's k_{TRP} transmissions are not blocked"}

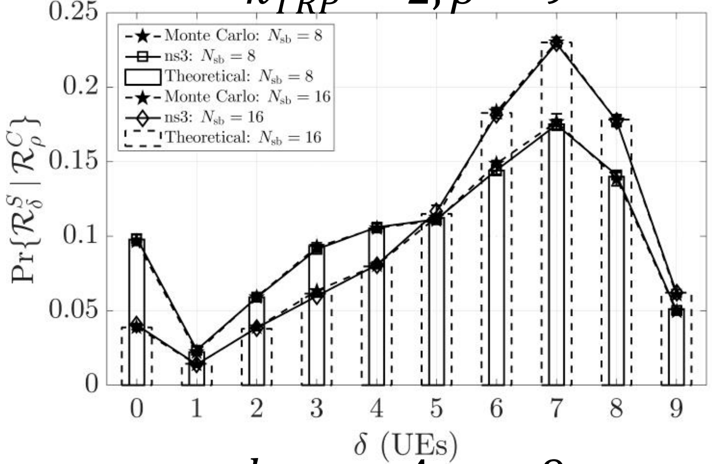
Pr{$\mathcal{R}^S_\delta \mid \mathcal{R}^C_\rho$ ∩ "s' receivers and σ interferers pick UE-of-interest's sub-band"}

Validation with MATLAB and ns-3

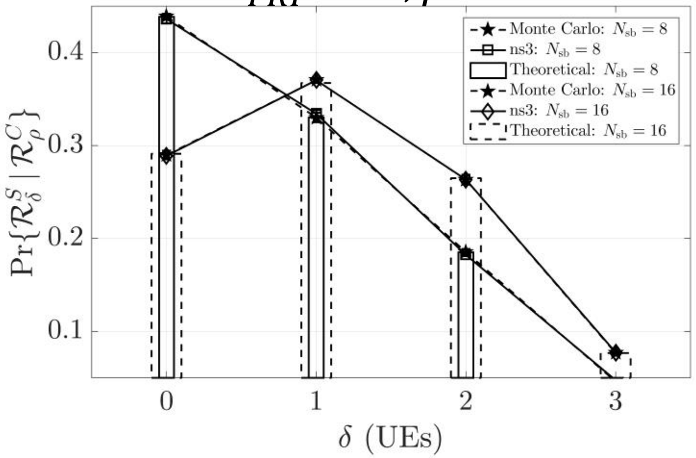
$k_{TRP} = 2, \rho = 3$



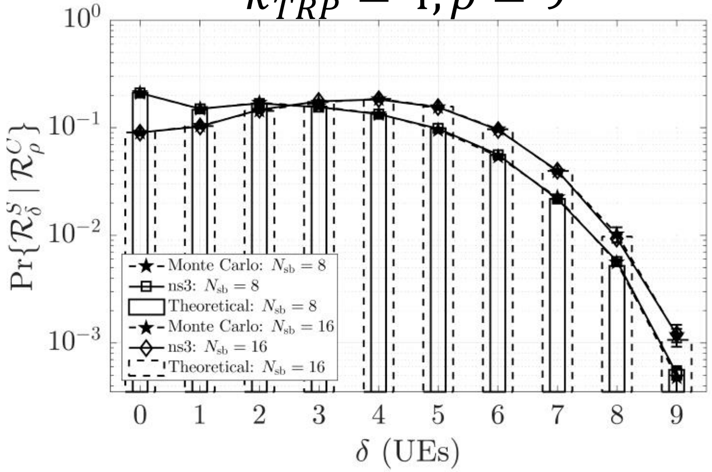
$k_{TRP} = 2, \rho = 9$



$k_{TRP} = 4, \rho = 3$



$k_{TRP} = 4, \rho = 9$



- Parameters:
  - $N_u = 11$ UEs
  - Shared Channel spans 50 PRBs (10 MHz)
  - $N_{sb} = 8, 16$ sub-bands
  - $k_{TRP} = 2, 4$ subframes
  - $\rho = 3, 9$ UEs
- Triad of aligned results within confidence intervals! ☺☺☺
- More sub-bands increases decoding probabilities
- $k_{TRP} = 4$: more masks (70 vs. 28) but collisions/half-duplex worse
- BUT: reduce k_{TRP} and you reduce throughput, everything else being equal

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Final Thought: The Impact of the Control Channel

	$N_{sb} = 8$ sub-bands		$N_{sb} = 16$ sub-bands	
	$k_{TRP} = 2$	$k_{TRP} = 4$	$k_{TRP} = 2$	$k_{TRP} = 4$
$\rho = 3$ UEs	(1.69, 1.11)	(0.84, 0.78)	(1.95, 0.91)	(1.13, 0.85)
$\rho = 9$ UEs	(5.07, 6.72)	(2.52, 3.96)	(5.86, 4.83)	(3.38, 3.83)

- Ordered pairs show (mean, variance) of δ
- Note that if ρ is small, not much impact from varying other parameters
- For larger ρ value, better to have $k_{TRP} = 2$
- More sub-bands is better, but this is within a limited bandwidth, so there is a throughput reduction (but number of devices decoding the message goes up)
- Our previous paper shows how to design the Control Channel so that the resource mapping defined by 3GPP allows us to eliminate the half-duplex problem (simple: set number of subframes to be greater than PRBs spanned by the Control Channel), so that the bottom row is the more likely outcome

Thank you!

Questions?

PSCR