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Signal processing: a networking perspective Part 2 – option A

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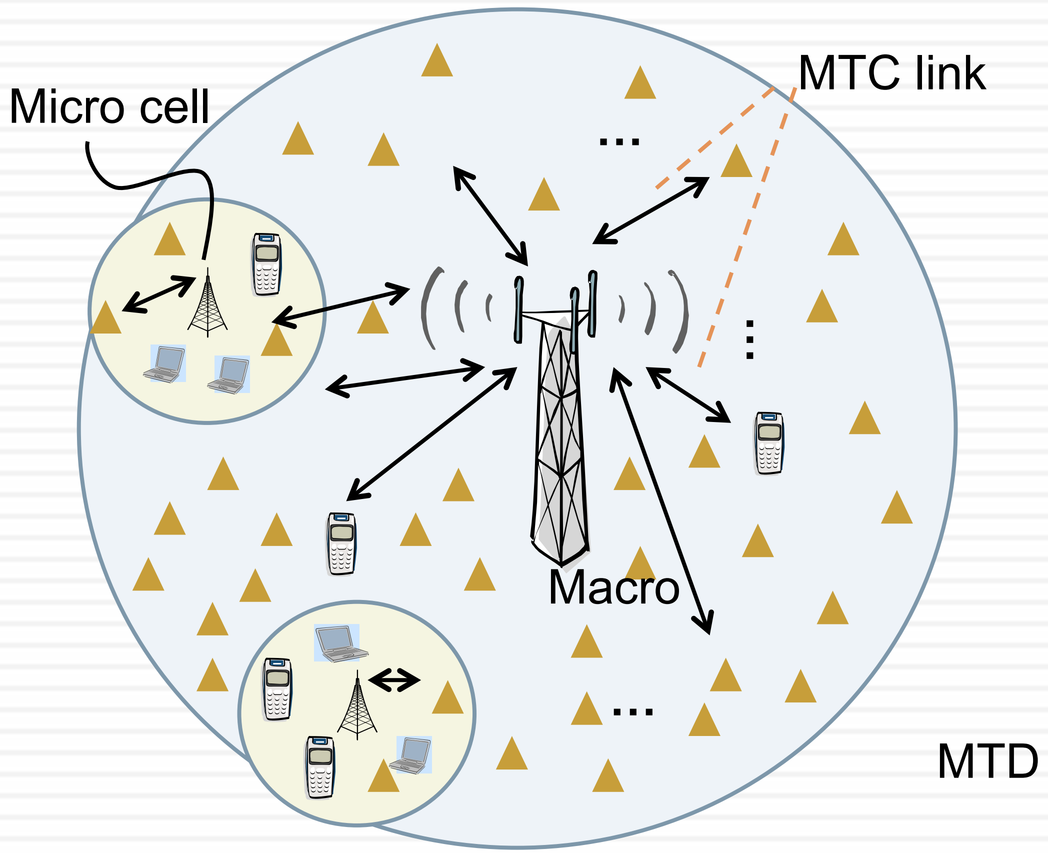
Outline

- **Part 2: Signal processing at PHY/MAC layers**
  - The challenge of massive M2M access
    - RFtag counting and identification
  - Interference models & system capacity
    - Multi-packet reception and Successive Interference Cancellation



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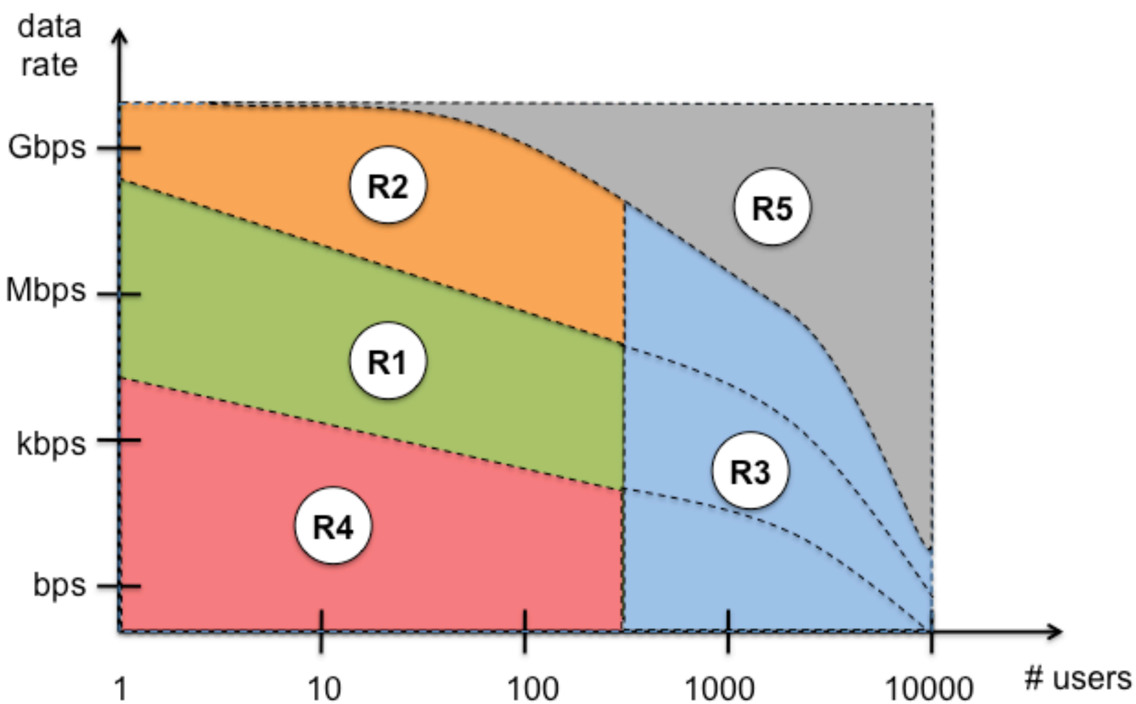
The challenge of massive M2M access

The shape of wireless to come



R1: today's systems

R2: high-speed versions of today's systems

R3: massive access for sensors and machines

R4: ultra-reliable connectivity at minimal rate

R5: physically impossible

5G=R1+R2+R3+R4

[Ref] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five Disruptive Technology Directions for 5G", IEEE Communications Magazine, February 2014.

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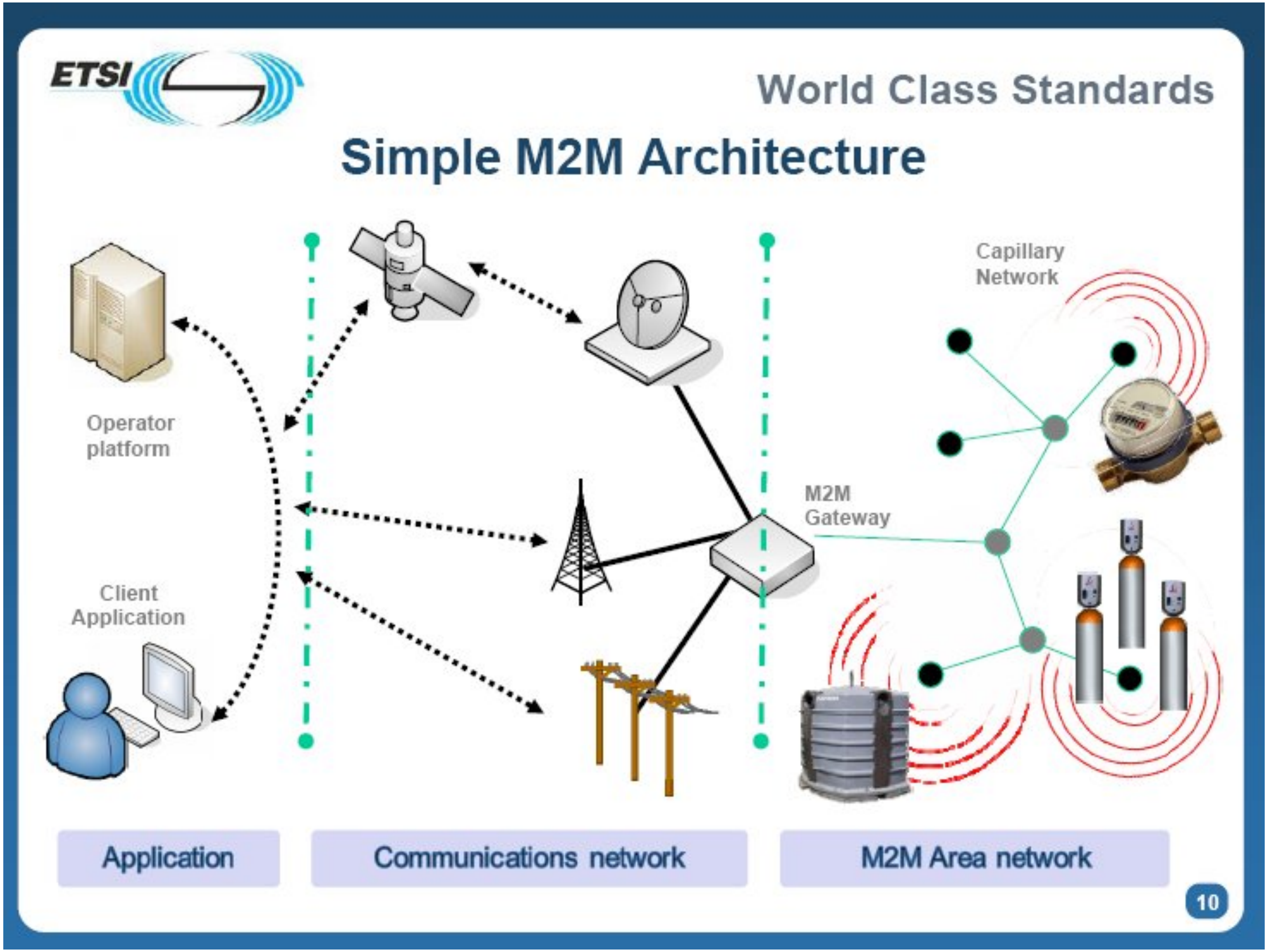
M2M reference architecture



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Machine Network Traffic

- M2M devices generate traffics of the following types
  - Periodic: smart metering application
  - Event-driven: emergency event report
  - Continuous: surveillance camera
- Large volume of different types of traffic at core network
  - Guarantee of diverse QoS traffic requirements
  - Reliability of both human-to-human and M2M traffic

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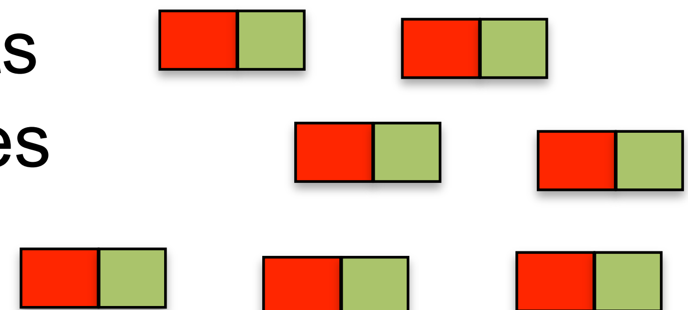
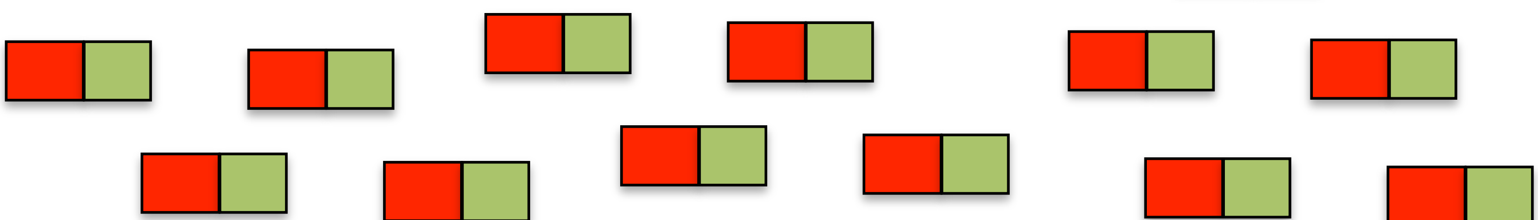
high-speed wireless vs. M2M

- high-speed systems built from information-theoretic principles with small control info and **large data**

- M2M require short data packets from massive number of devices each transmitting sporadically





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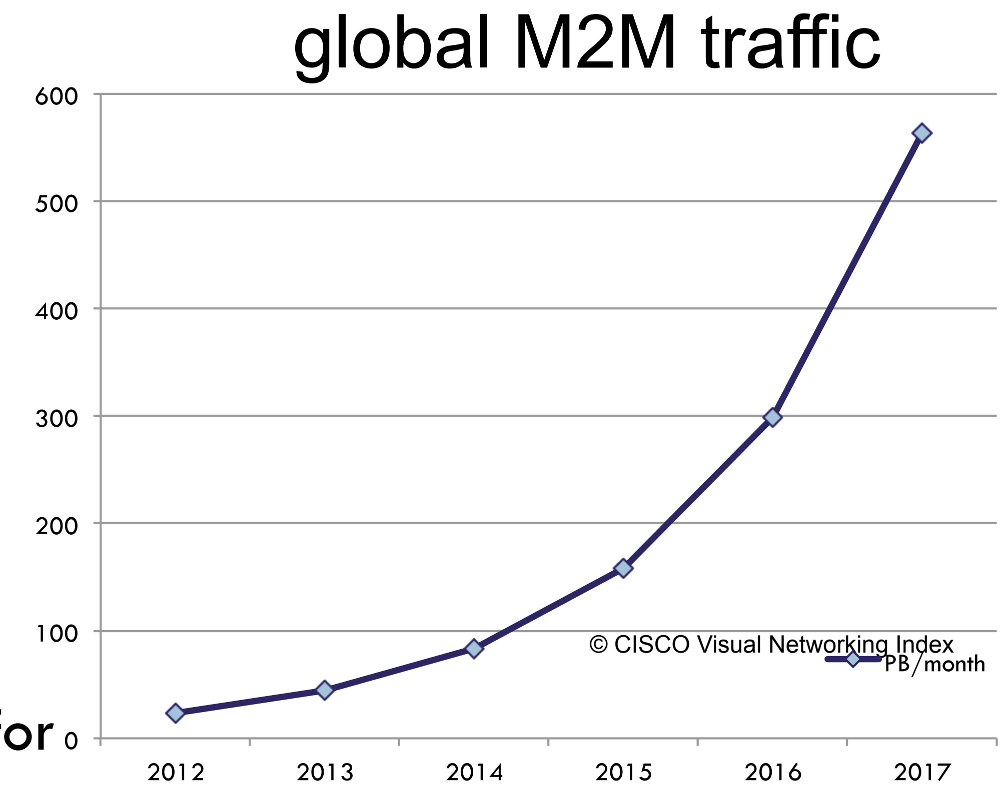
enormous M2M growth expected

- 24-fold traffic growth from 2012 to 2017
- 4.6-fold growth of M2M #subscriptions
  - from 369 million in 2012 to 1,7 billion in 2017
- M2M traffic will account for approximately 5 % of overall mobile traffic in 2017



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The batch resolution problem

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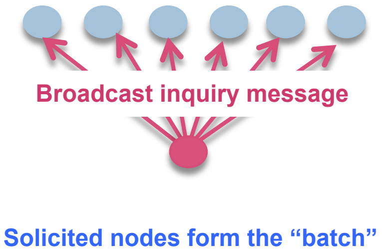
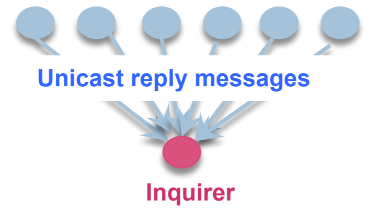
Problem statement

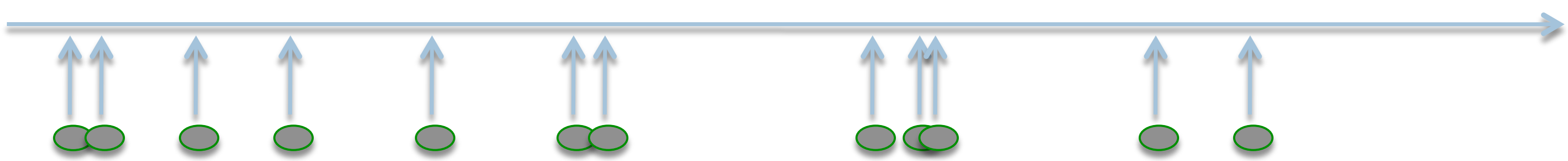
- What's a "batch"?
  - Set of mutually interfering nodes simultaneously solicited to send a packet
    - RF tags illuminated by a reader
    - Wireless nodes that reply to neighbour-discovery request
    - Mobile terminals that compete to reserve a channel slot
- What's the "Batch resolution problem"?
  - Simultaneous transmissions by multiple nodes result into collision ➔ all packets are lost!
  - Nodes need to arbitrate the channel access in order to transmit their packet avoiding collisions
    - A node that successfully transmits is said to be **resolved**
- What's a "Batch Resolution Algorithm" (BRA)?
  - The BRA arbitrates the channel access in order to minimizing the batch resolution interval, ie, the mean time required to resolve all the nodes in the batch



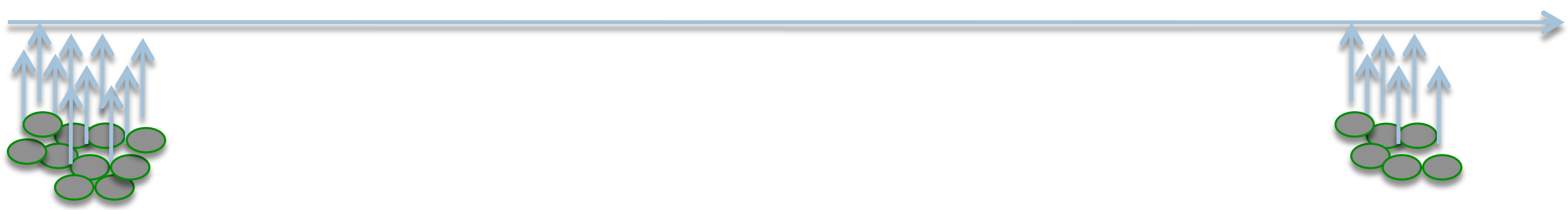


Batch resolution problem vs MAC

- The batch resolution problem resembles the MAC problem but…
  - MAC protocols generally look at the channel contention as a *steady-state phenomenon*



  - BRAs address scenarios where contention has a bursty nature



Performance measures

- Batch resolution interval (BRI)
  - T(n) = E[time required to resolve a batch of size n]
- Batch Throughput

$$\lambda(n) = \frac{n}{T(n)}$$

- Asymptotic throughput $\Lambda = \lim_{n \to \infty} \lambda(n)$
  - Maximal sustainable arrival rate when BRA is used as *obvious MAC:*
    - solve a batch and queue packets arriving in the meanwhile, the form the next batch (gate policy)

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Splitting-tree BRAs

- Time is slotted
  - Slots may have unequal duration in CSMA networks
- In each slot, some nodes are **activated**, i.e., transmit
- **Immediate feedback:** returned after each slot
  - Idle slot: no nodes transmit
  - Successful slot: a single node transmit
  - Collided slot: two or more nodes transmit
- BRA works recursively, driven by feedback

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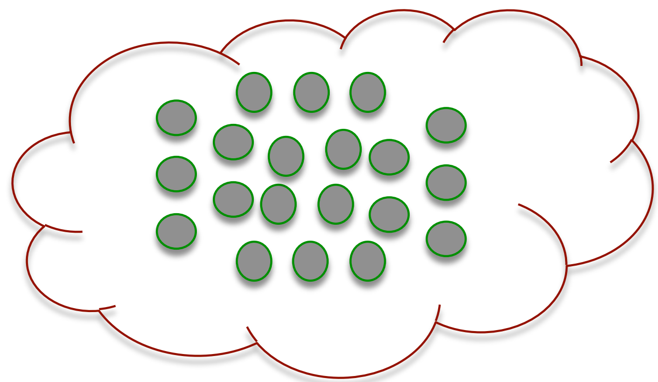
Divided batch in “m” subgroups

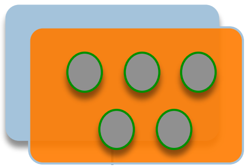


Initial batch
(expected size m_n)

Subgroup 1 Subgroup 2 Subgroup m

(expected size $g=m_n/m$ optimal)

Slot1: collided



Initial batch: {1,2,3,4,5}

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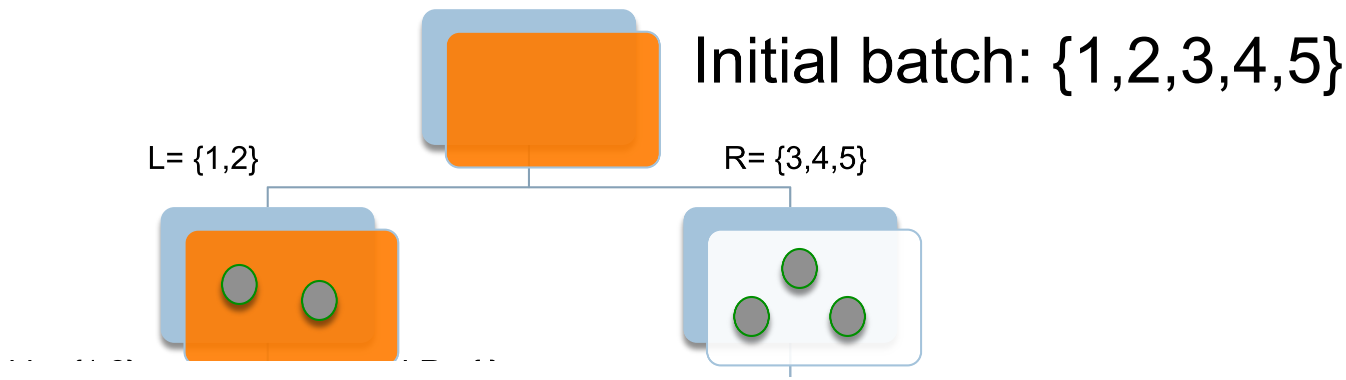
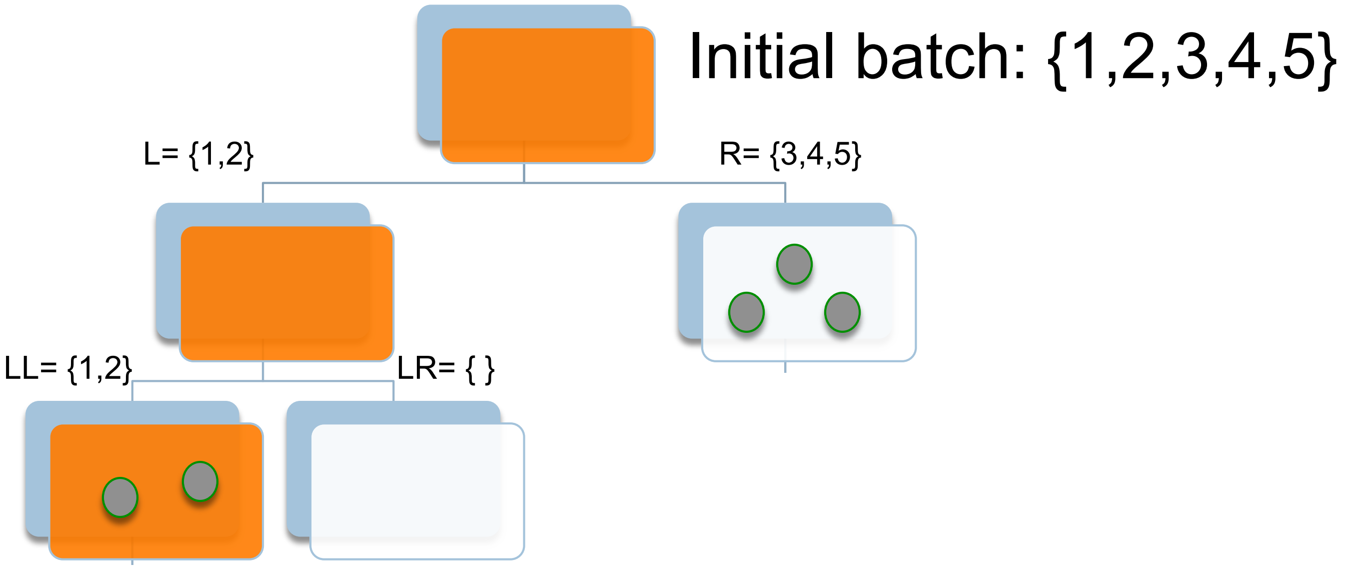
Slot2: collided



Slot3: collided



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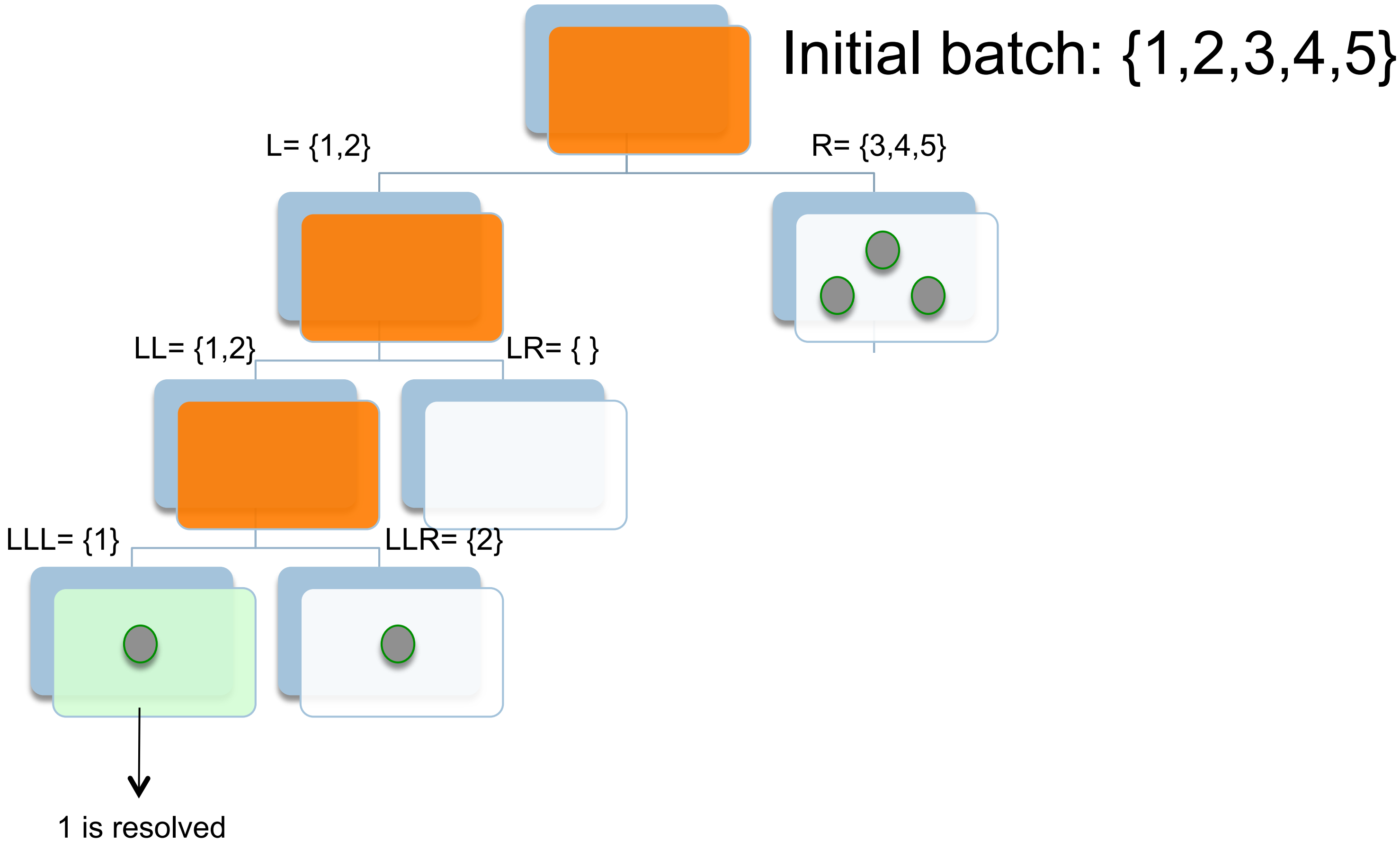
Slot4: successful



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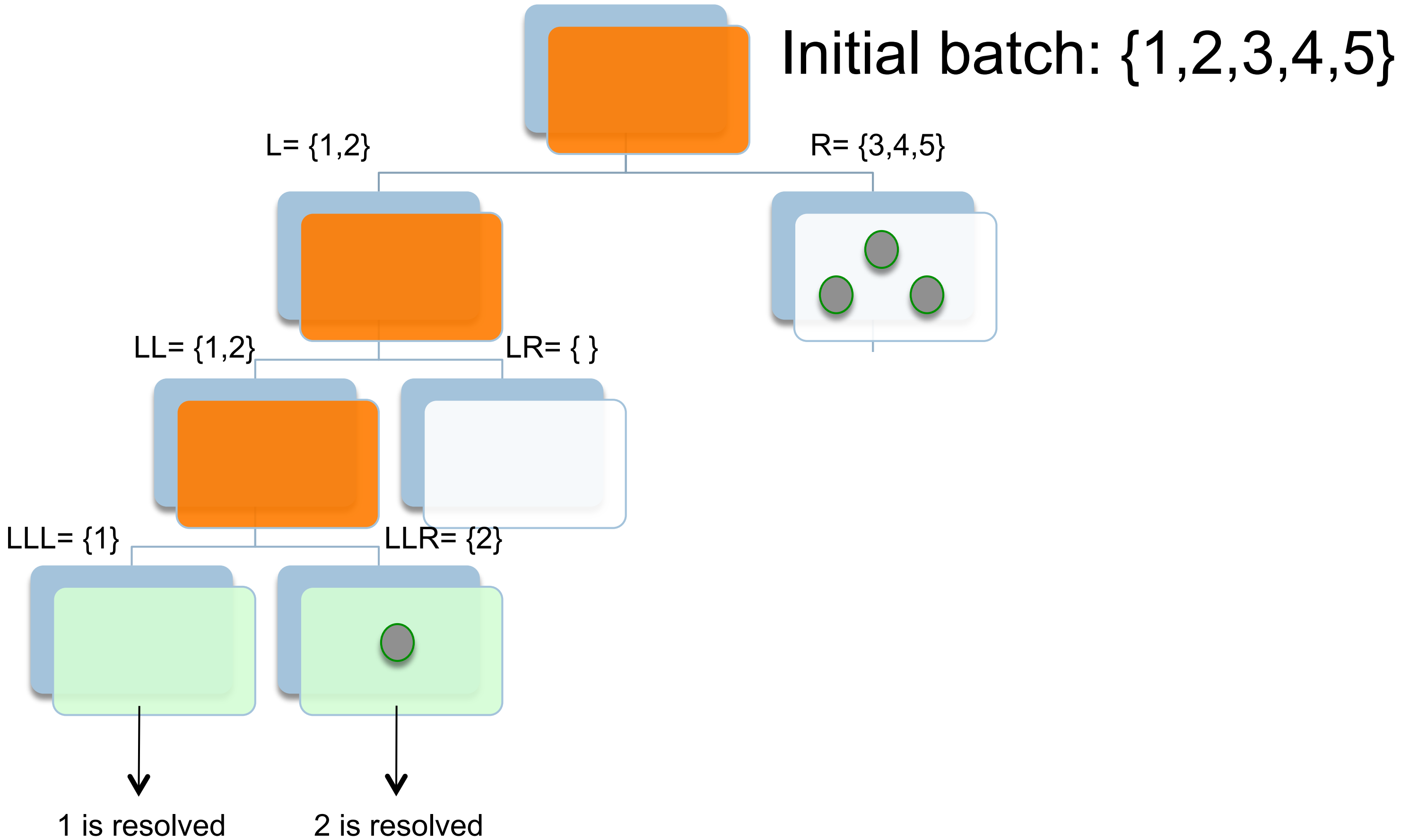
Slot5: successful



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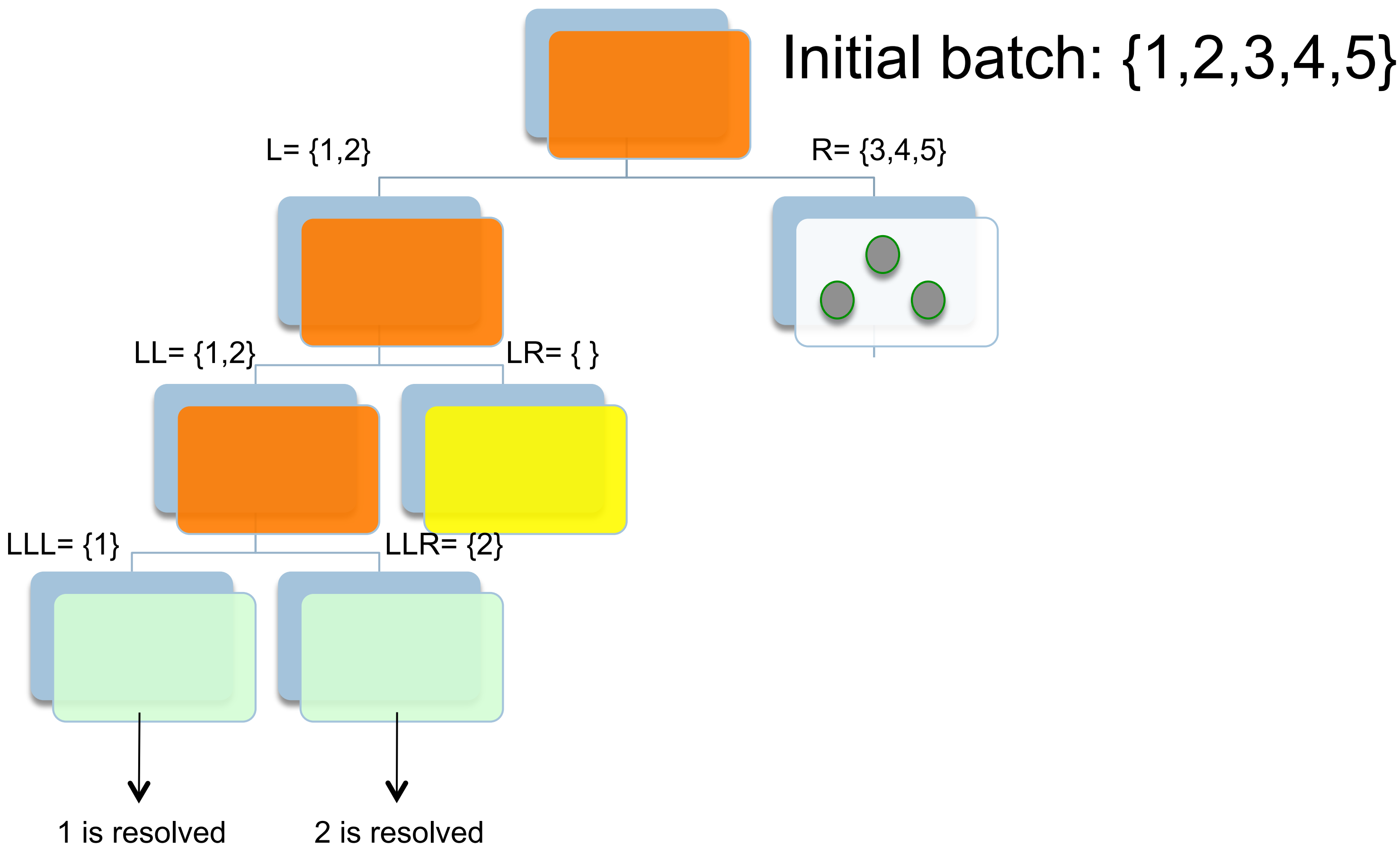
Slot6: idle



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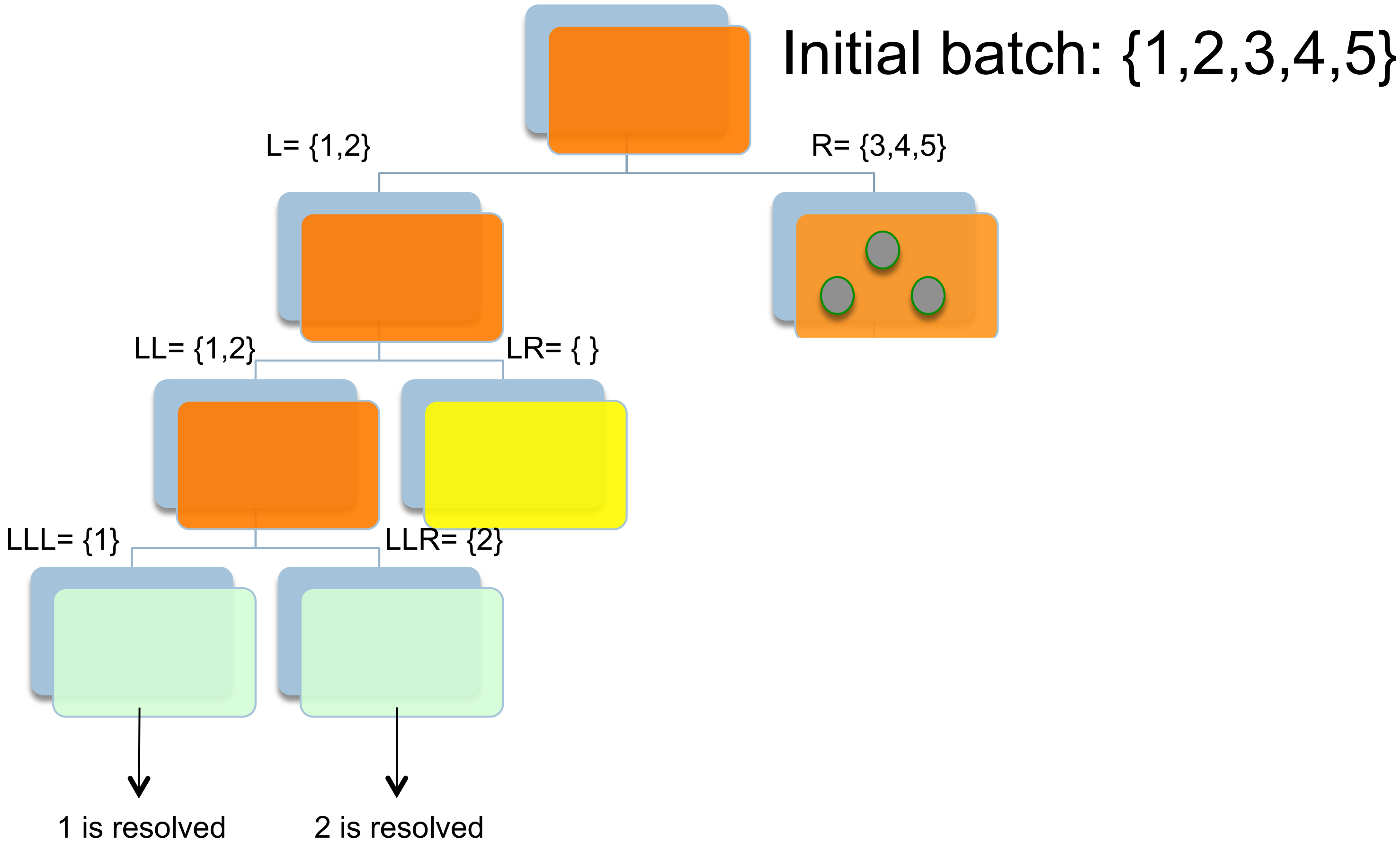
Slot7: collided



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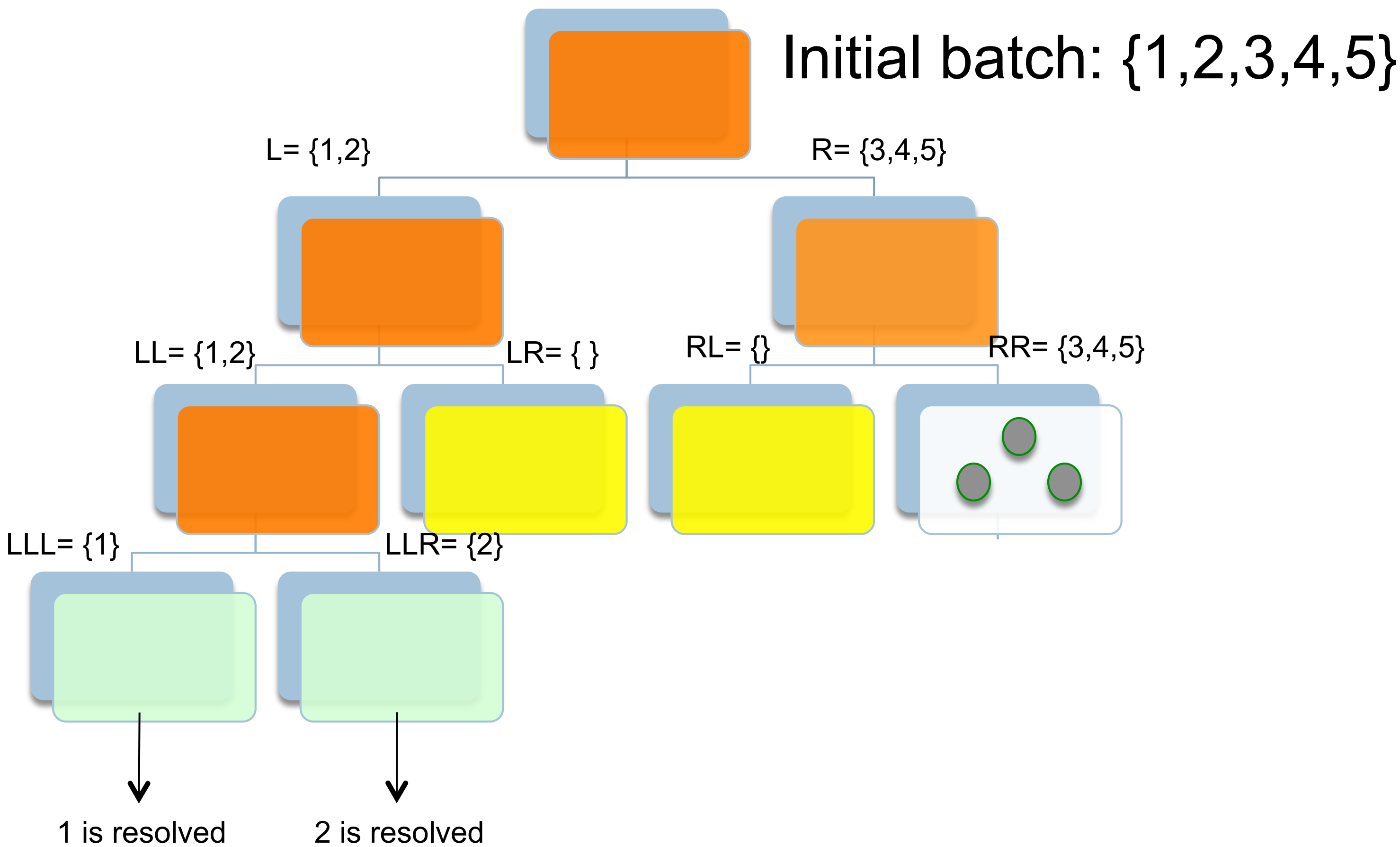
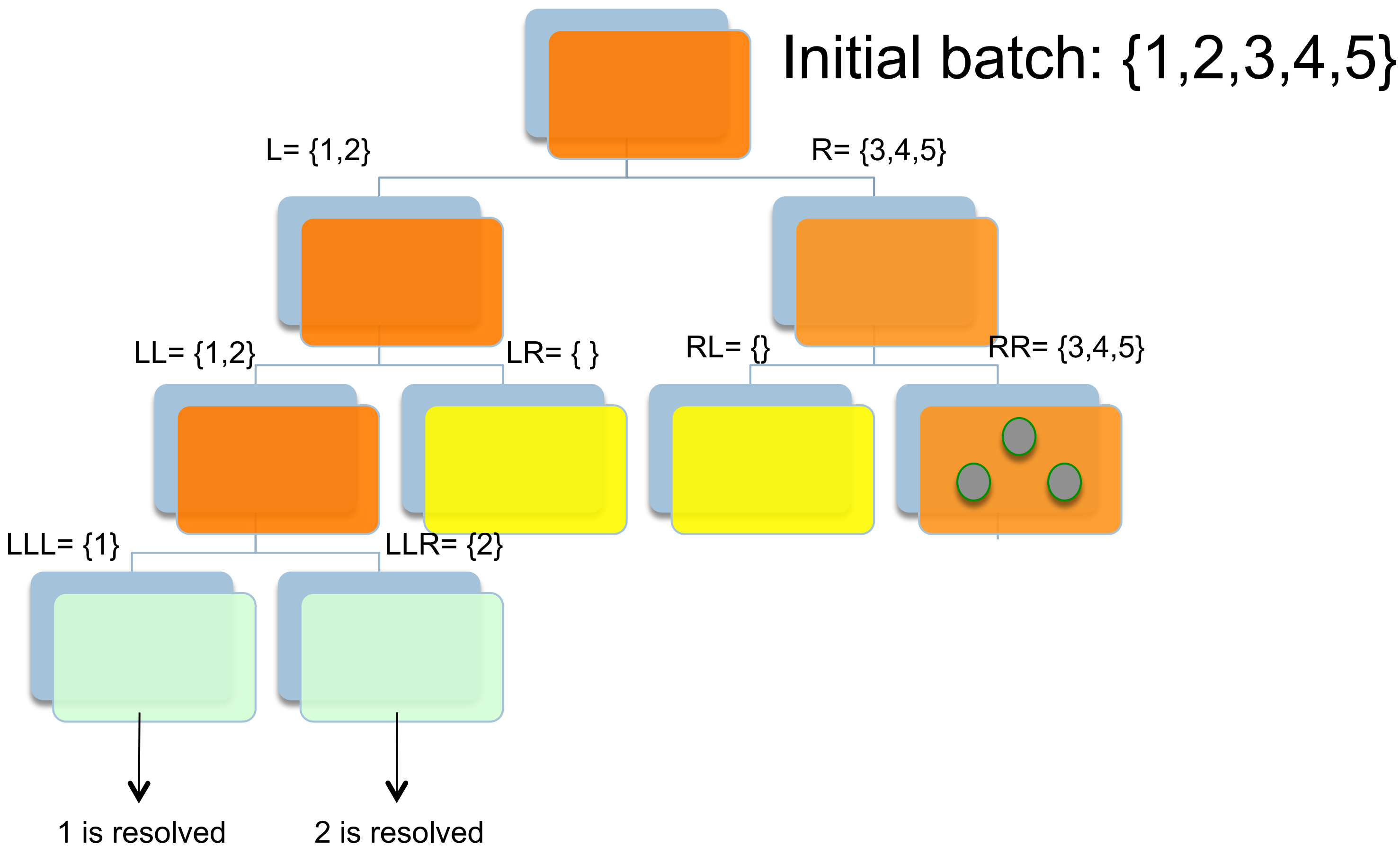
Slot8: idle



Slot9: collided



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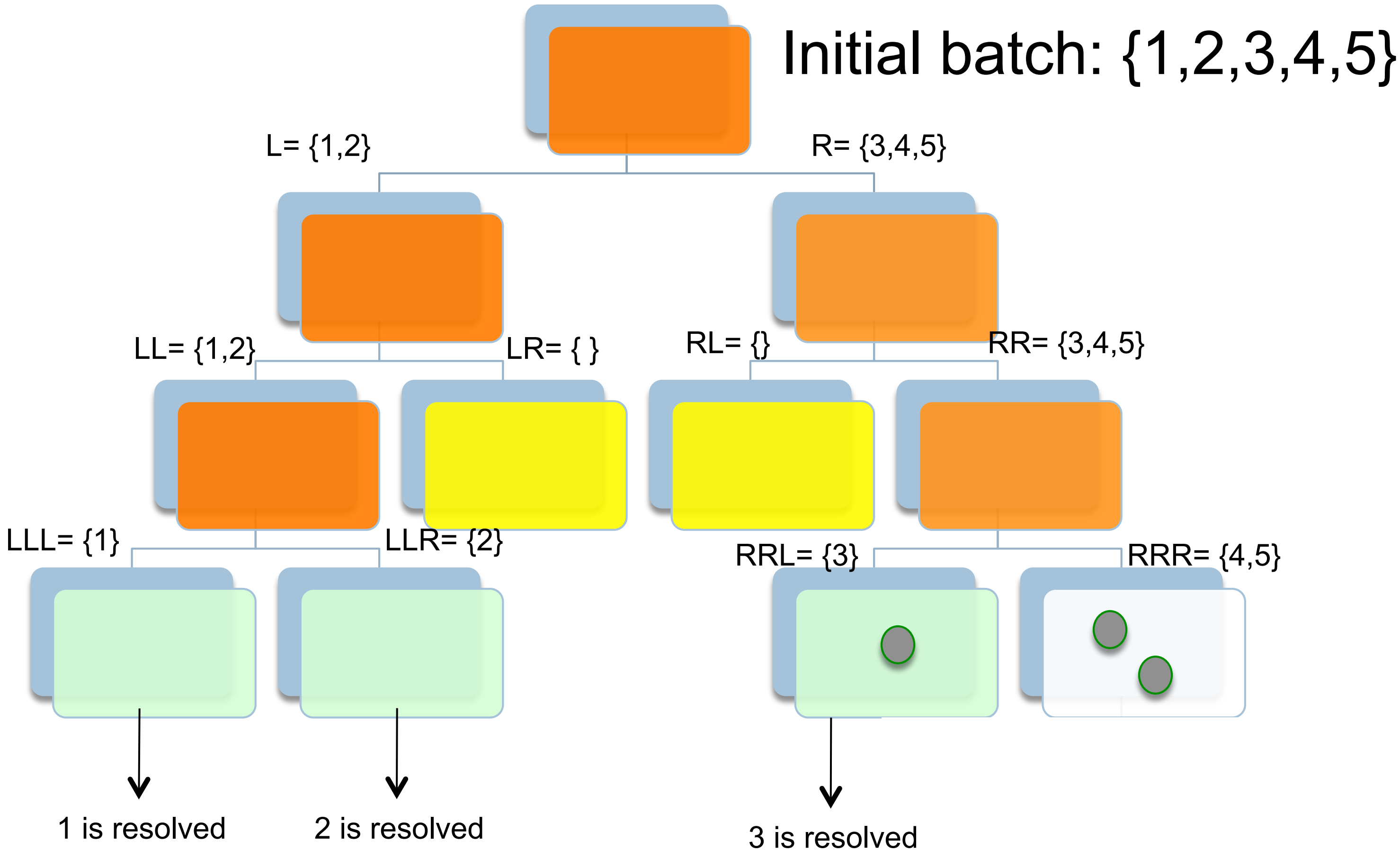
Slot10: successful



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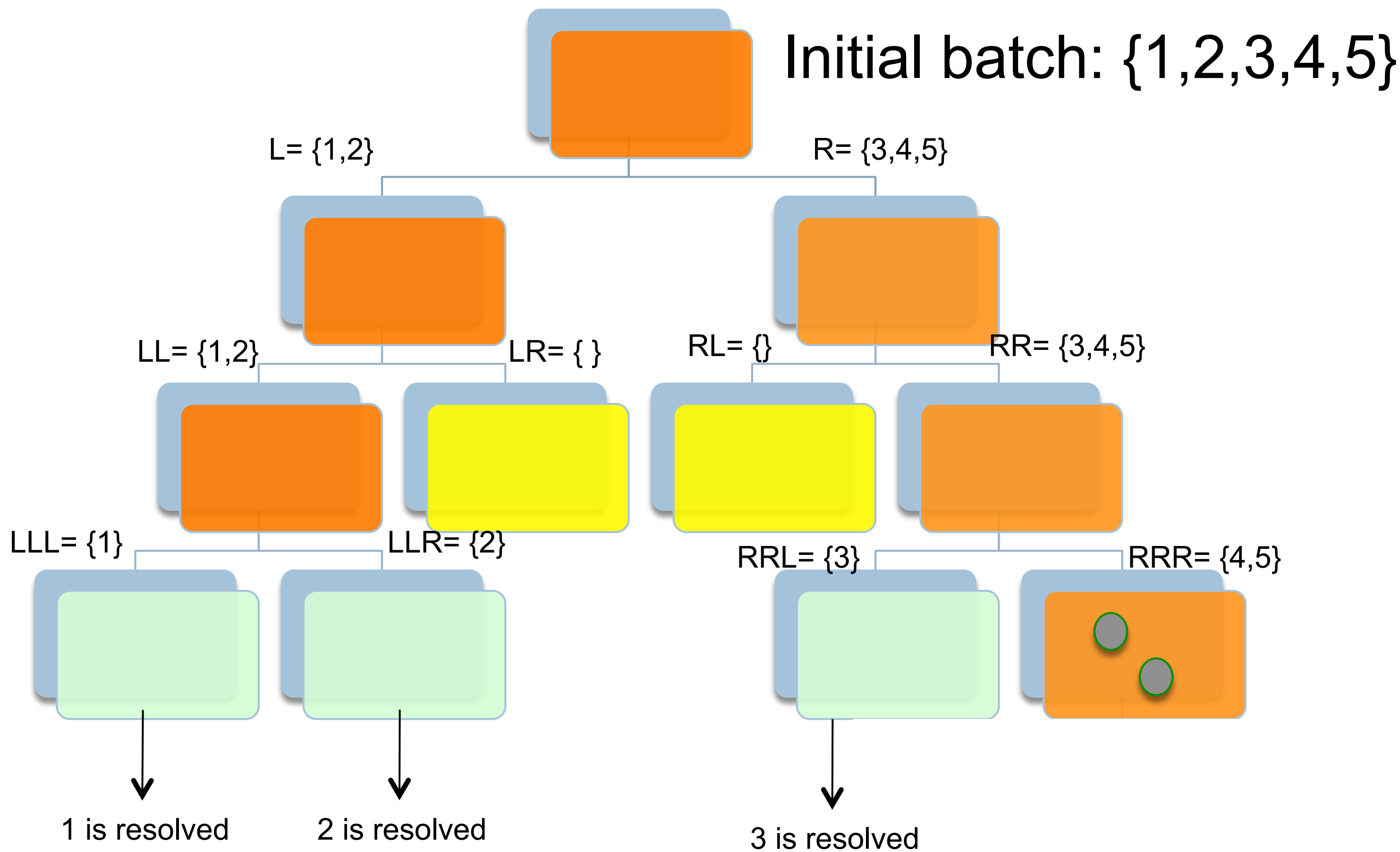
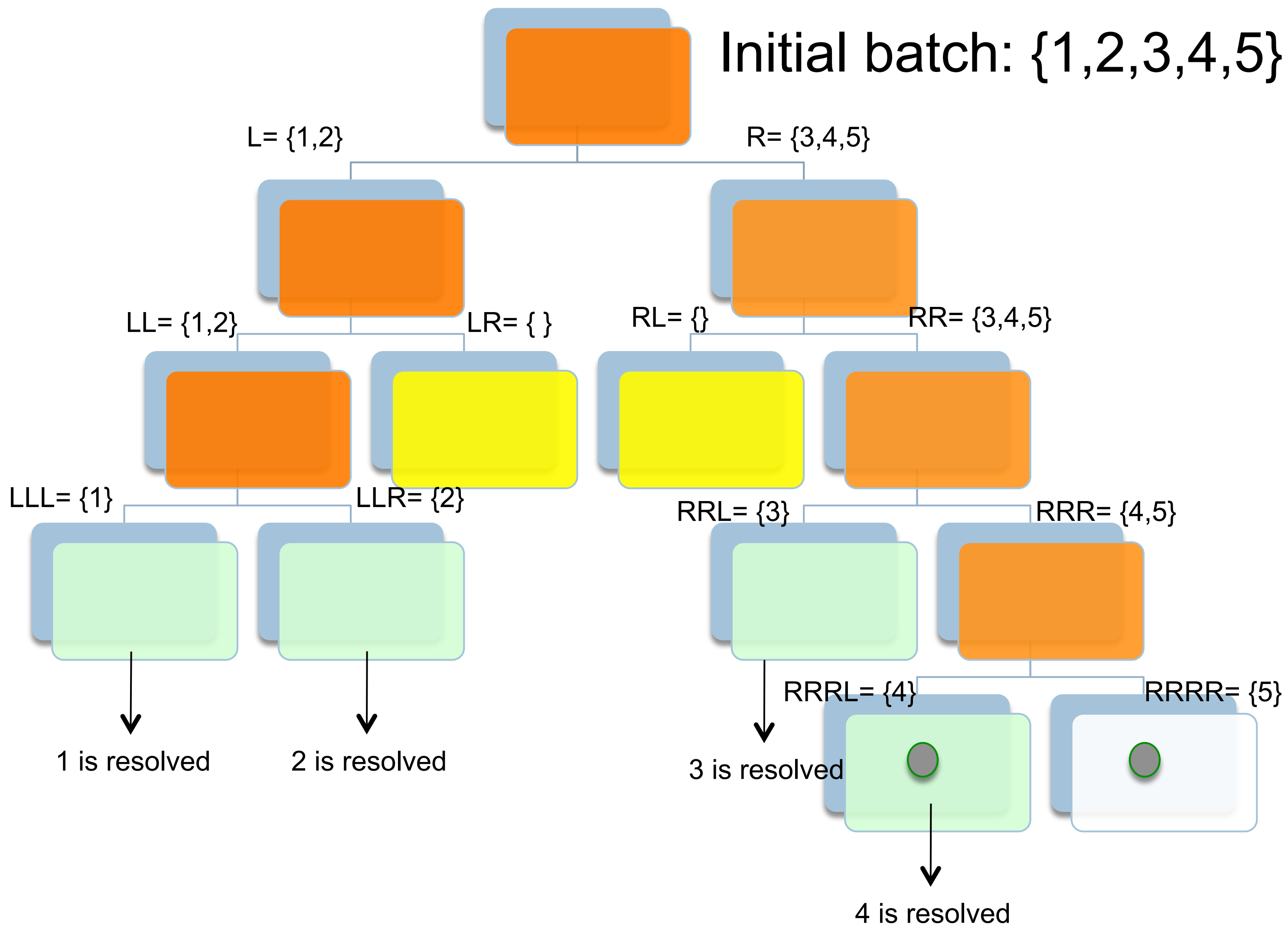
Slot11: collided



Slot1 2: successful



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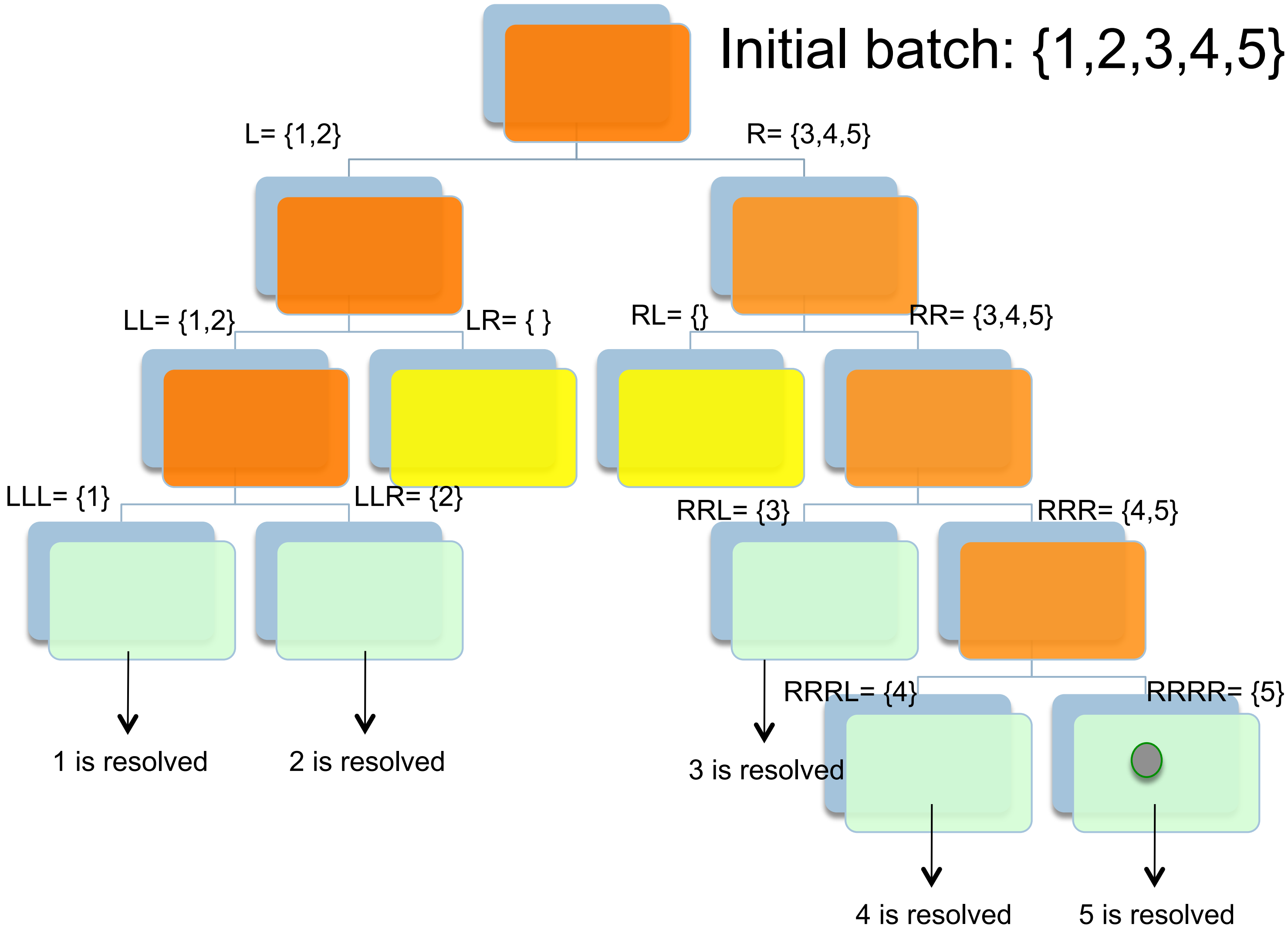
Slot13: successful



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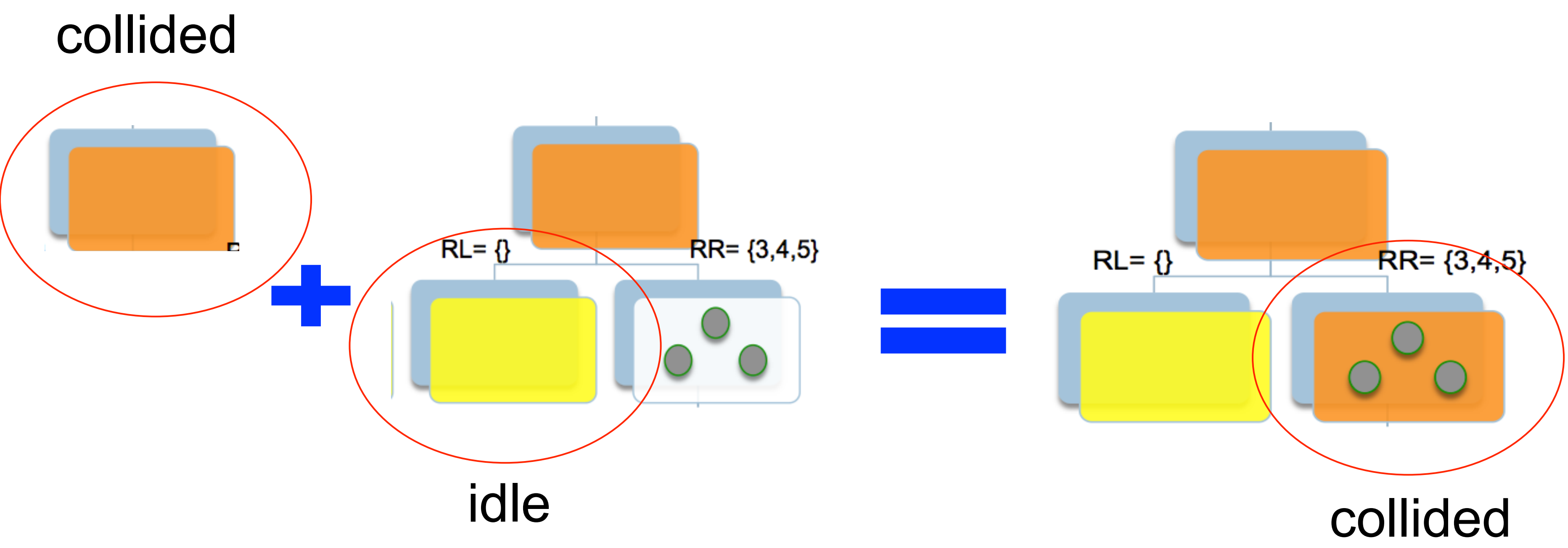
Modified Binary Tree

- Avoid predictable collision
  - A "collided→idle" sequence is always followed by a collided slot!



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Modified Binary Tree

- Solution: ***virtualize predictable collisions***

- Any time a collided slot is followed by an idle slot, do not activate the right subset, but rather, split it in two subsets *as if a collision had occurred* (but without wasting a slot)

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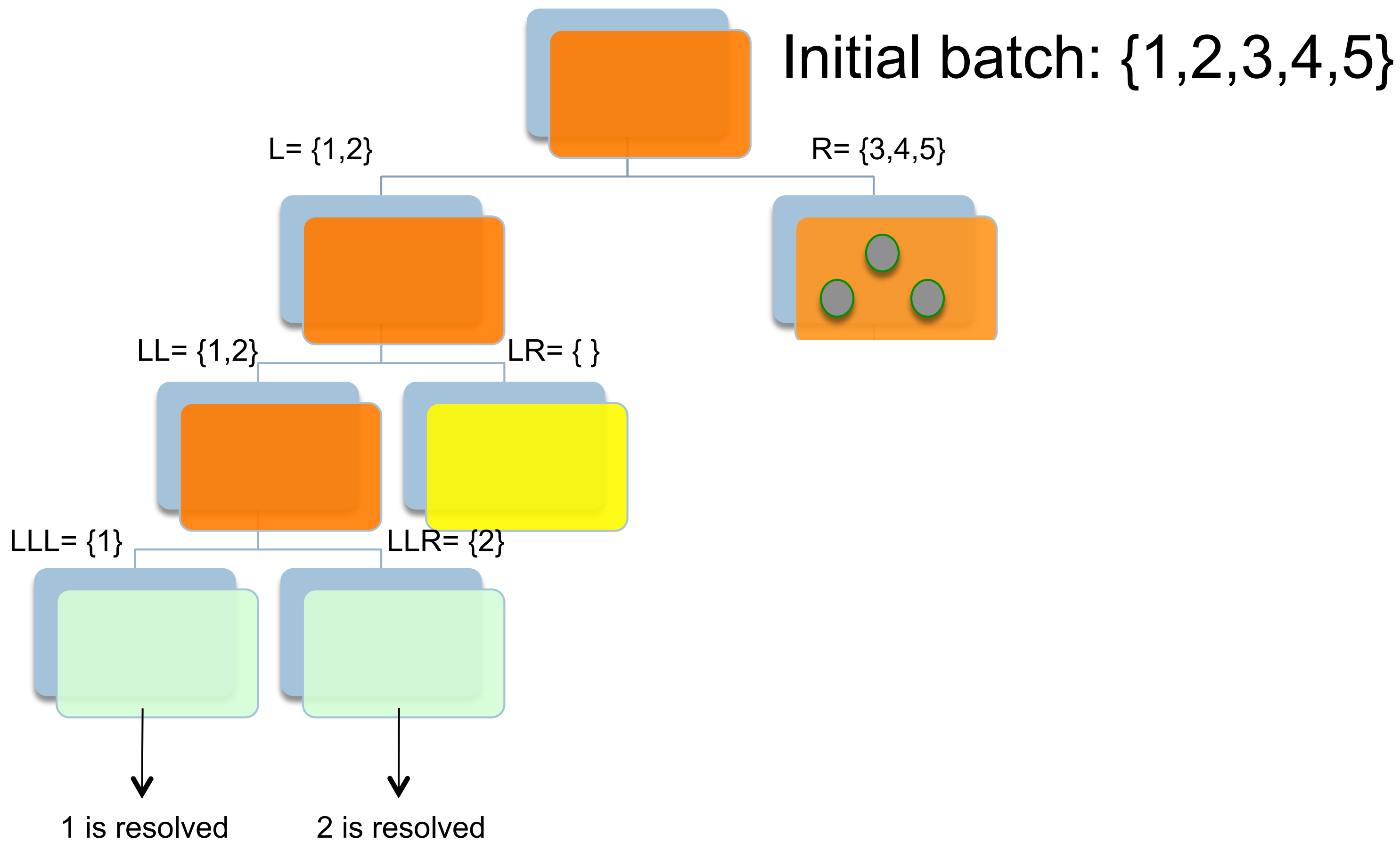
Slot7: collided



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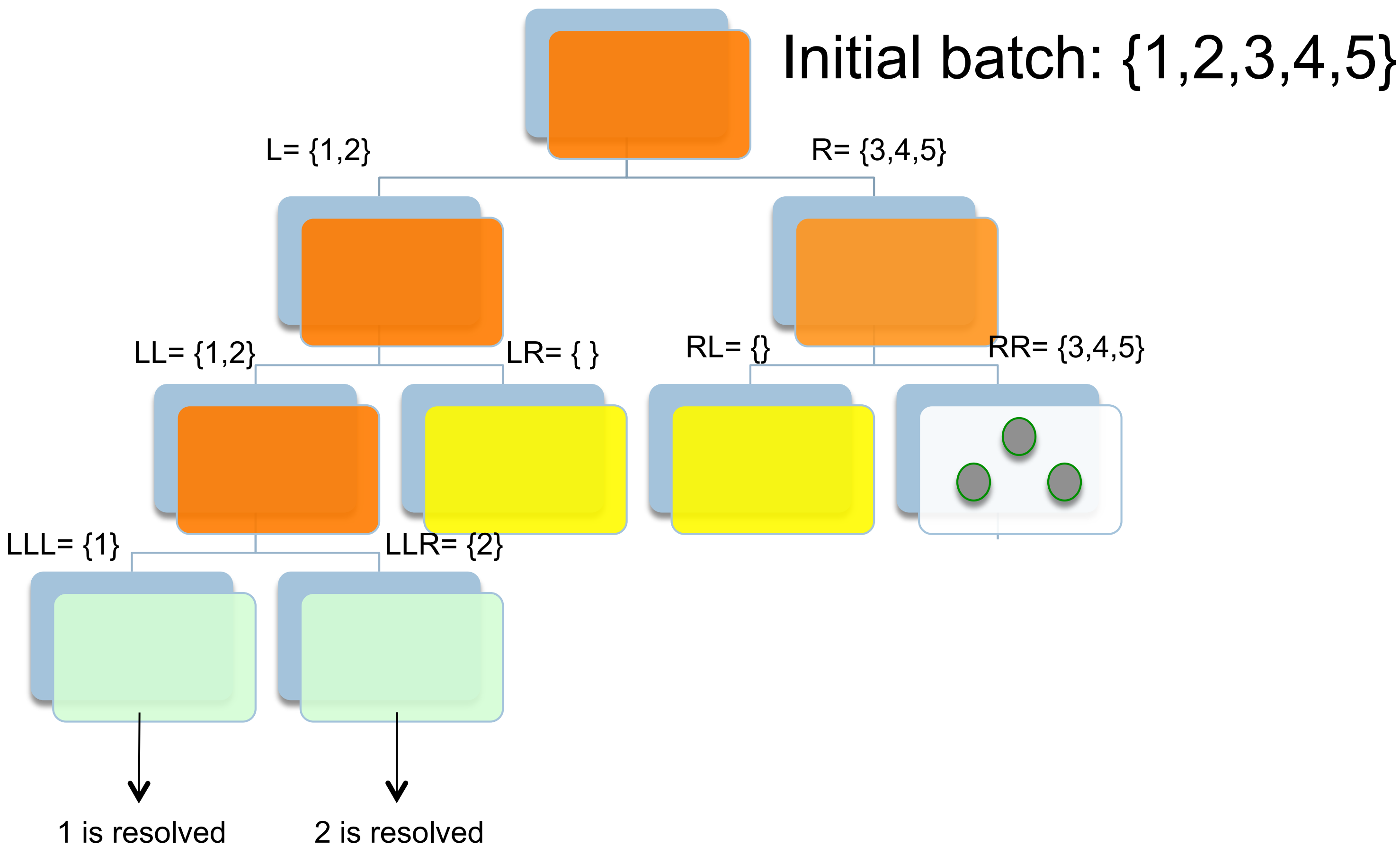
Slot8: idle → split immediately!!!



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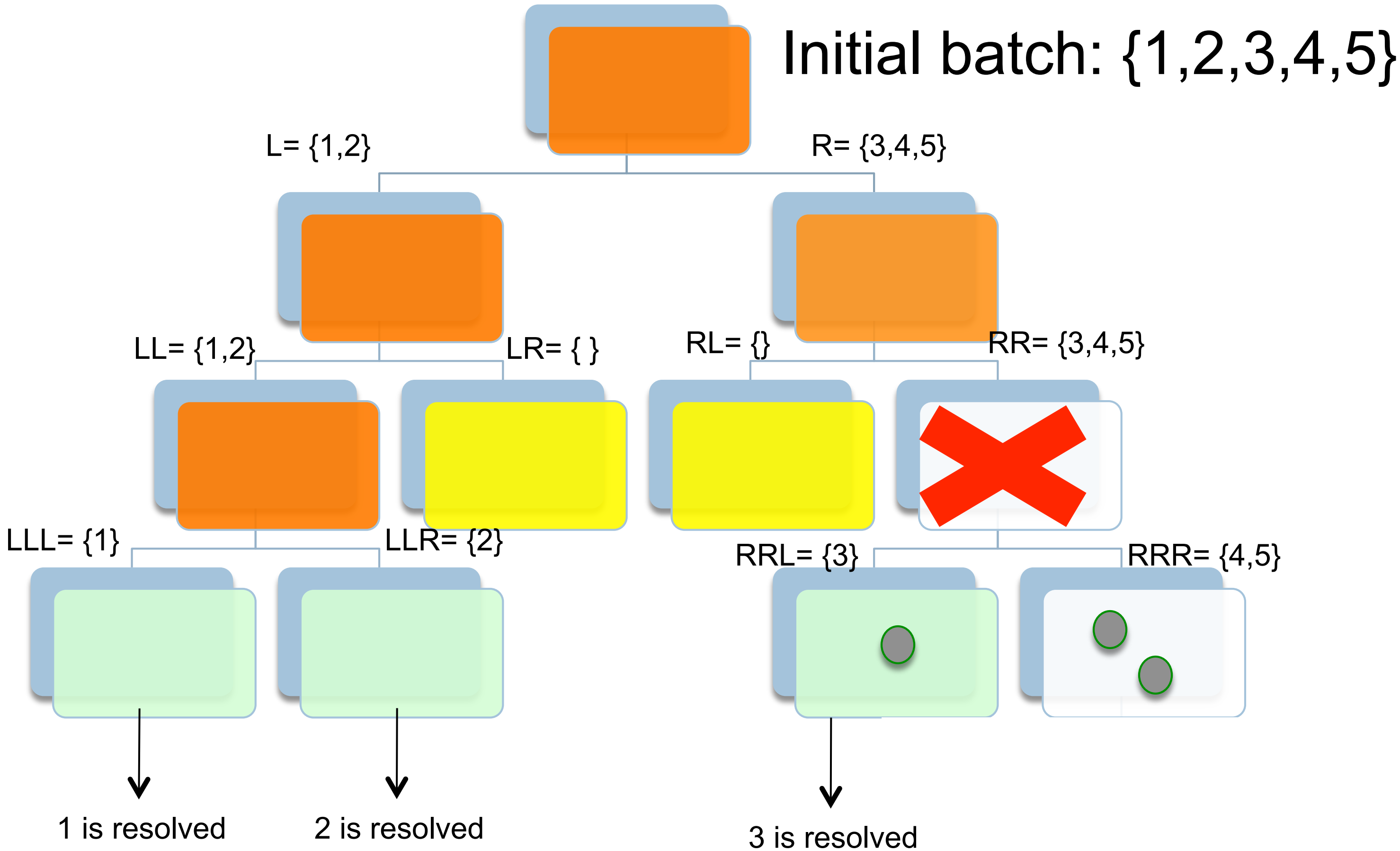
Slot9: successful



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Clipping mechanism

- Valid for batches with **Poisson distributed size**
- When a collided slot is followed by another collided slot, the right branches of the tree can be clipped
  - The second collision "erase" the prior information on the cardinality of the nodes in the right subsets
  - It is more convenient to return these nodes to the original set and divide again in optimal subsets

Rationale

- Let X be the size of the activated interval
  - X is a Poisson rv with parameter m
- Imagine to split BEFORE observing the outcome
  - L and R are independent Poisson rvs with parameters *mp* and *m(1-p)*
- Now, you observe a collision → X>1 → R is not Poisson!

  Pr[R=k | L+R >1]
- If another collision → L>1 → R is again Poisson!

  Pr[R=k | L+R >1, L>1] = Pr[R=k | L>1] = Pr[R=k]

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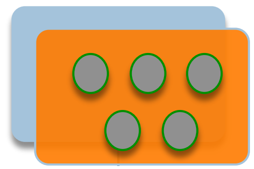
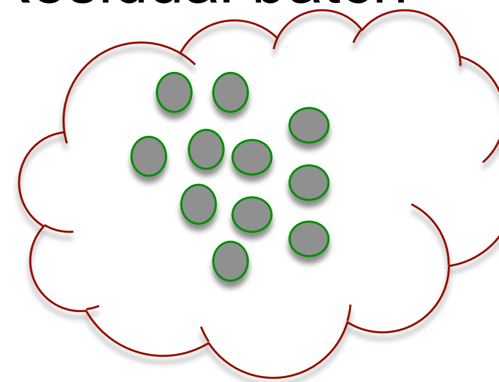
Slot1: collided

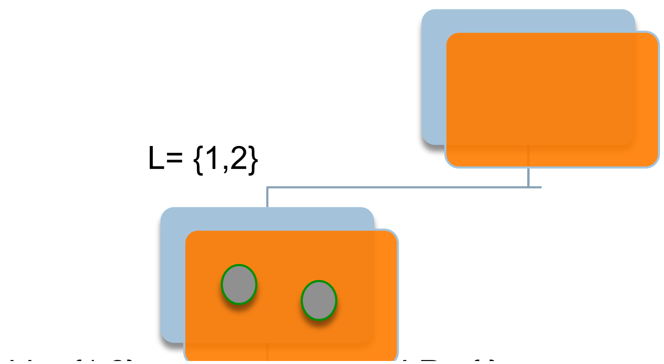
subgroup: {1,2,3,4,5}



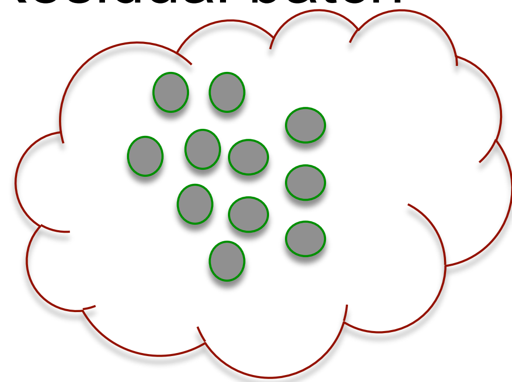
Residual batch



Slot2: collided



Residual batch



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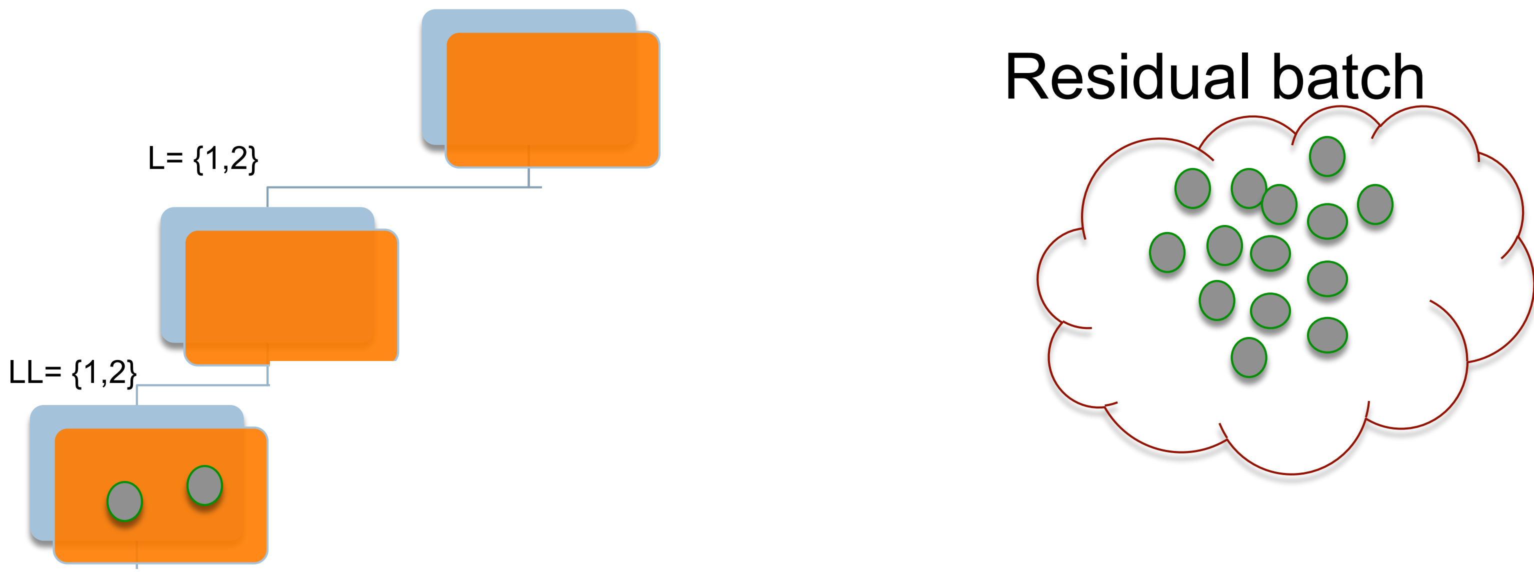
Slot3: collided



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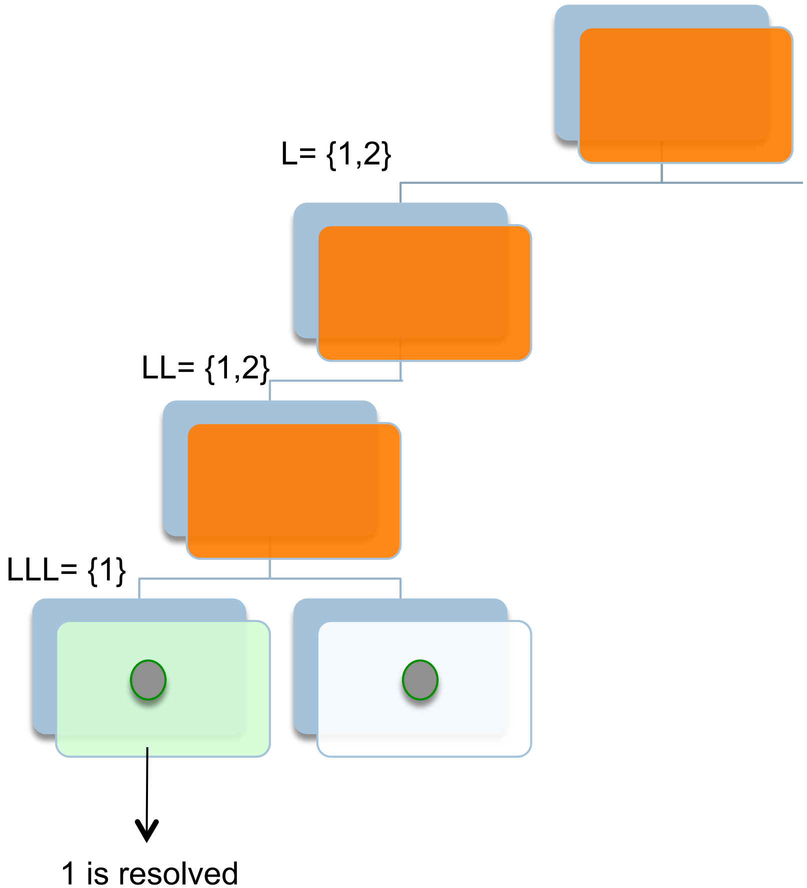
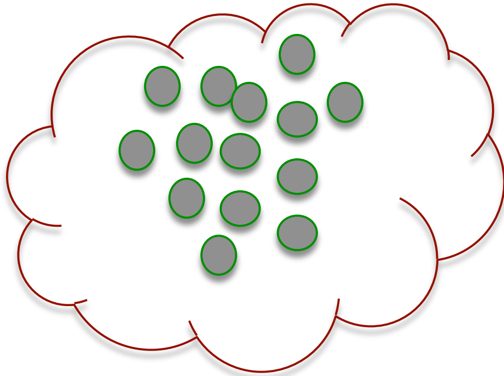
Slot4: successful



Residual batch



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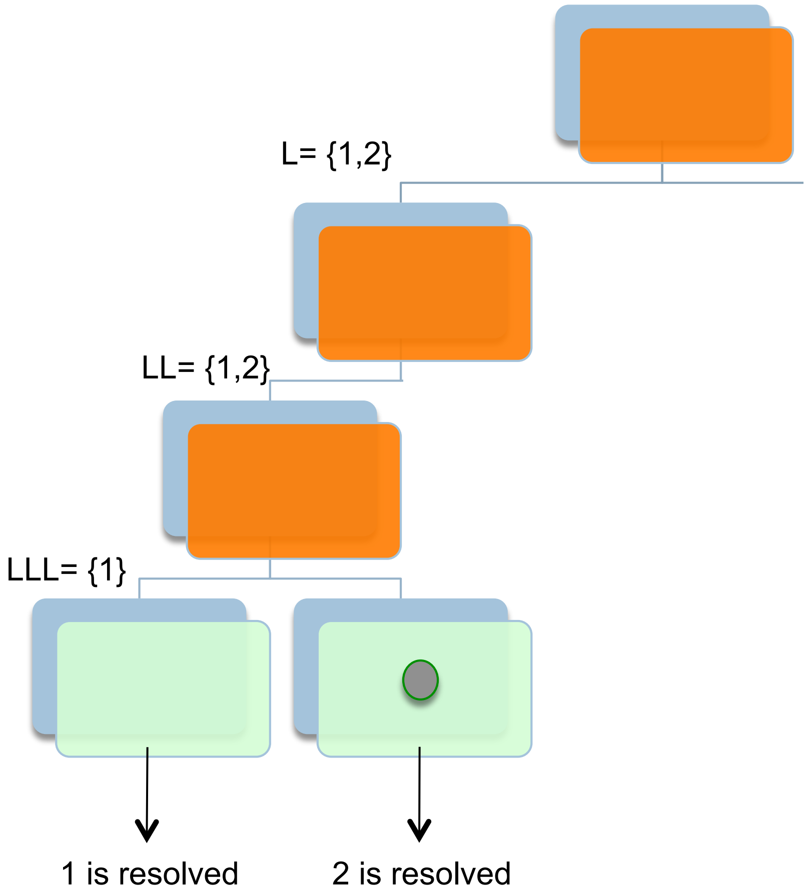
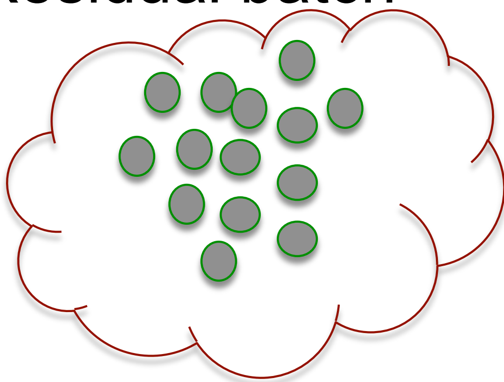
Slot5: successful



Residual batch



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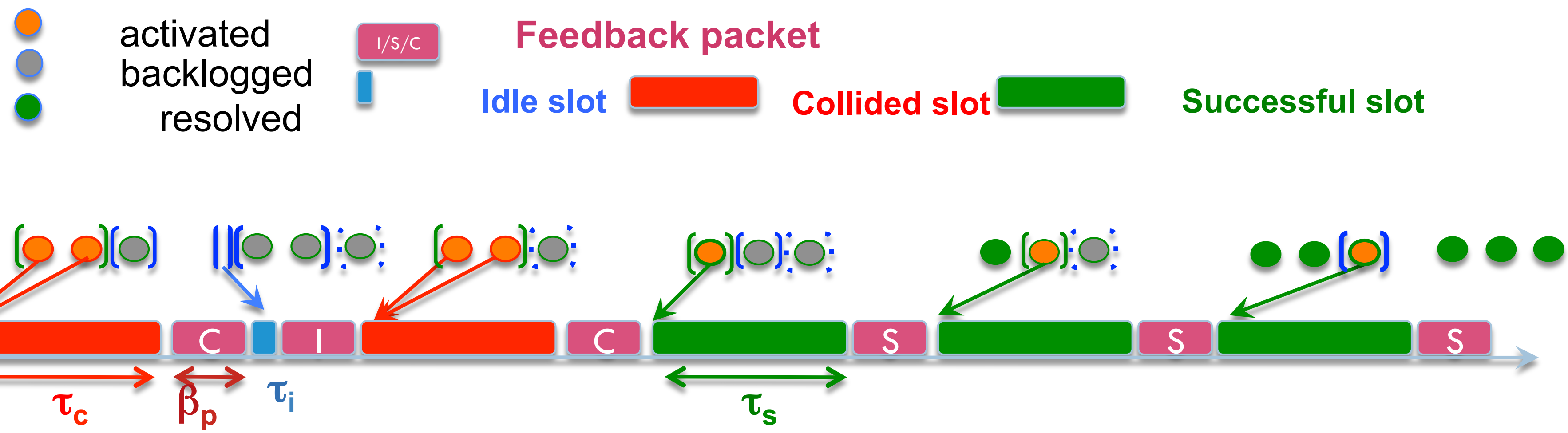
Interval Estimate Collision Resolution algorithm (IECR)

- CMBT is optimal if mean batch size m_n is known
- If the batch size is unknown, it must be estimated before applying CMBT
- IECR couple CMBT with a **batch size estimate phase**
  - Apply CMBT to whole batch until the first successful transmission
  - Estimate the residual batch size *n* on the basis of the number of consecutive collisions undergone so far
  - Repeat by assuming *n* as estimated above

Timing

Event	Slot duration	Feedback duration		
			Classical	Practical (CSMA)
Successful	Tdata=1	ϕ_s	negligible	*significant*
Idle	β_i<<1	ϕ_i	negligible	negligible
Collision	β_c~1	ϕ_c	negligible	*small*



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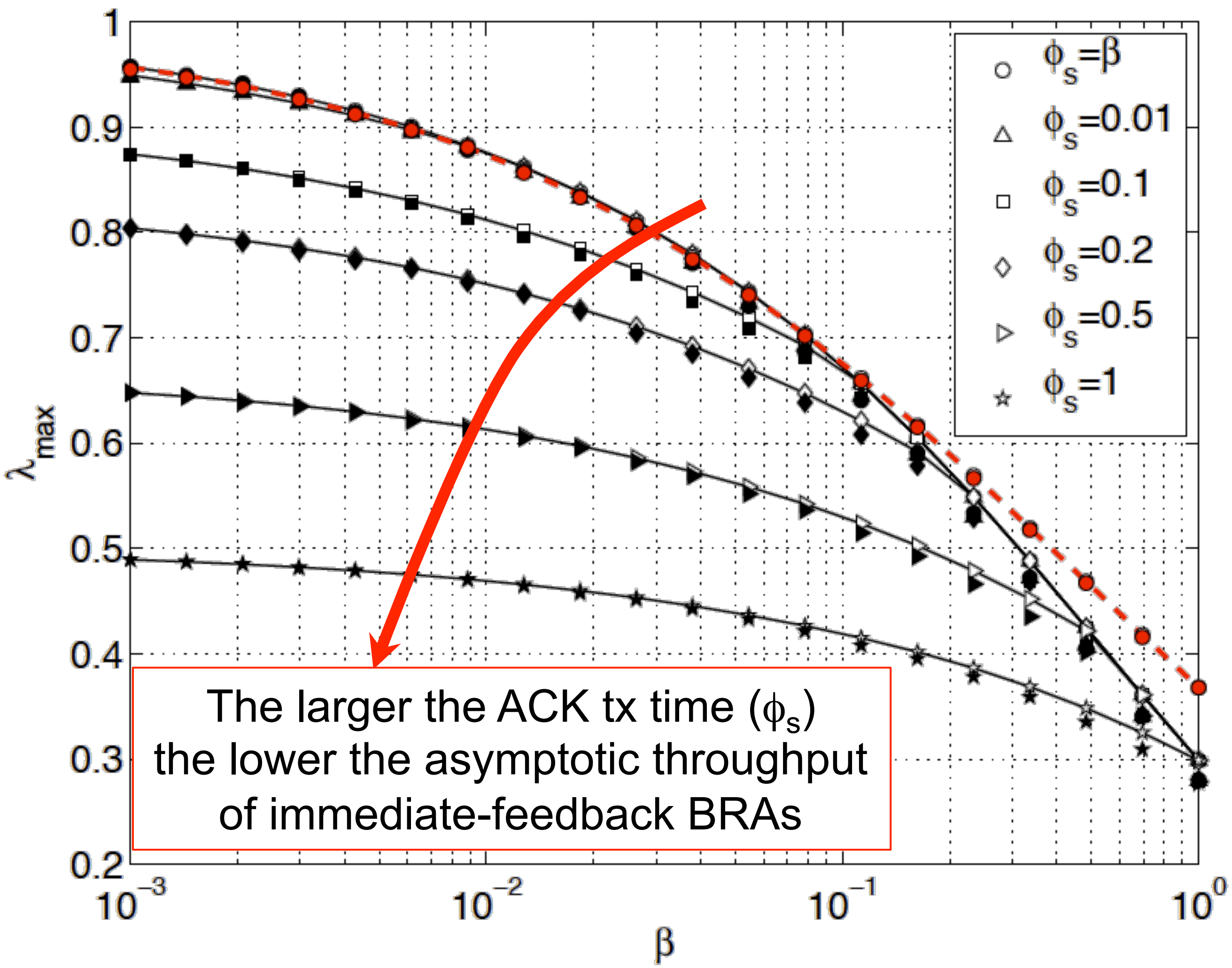
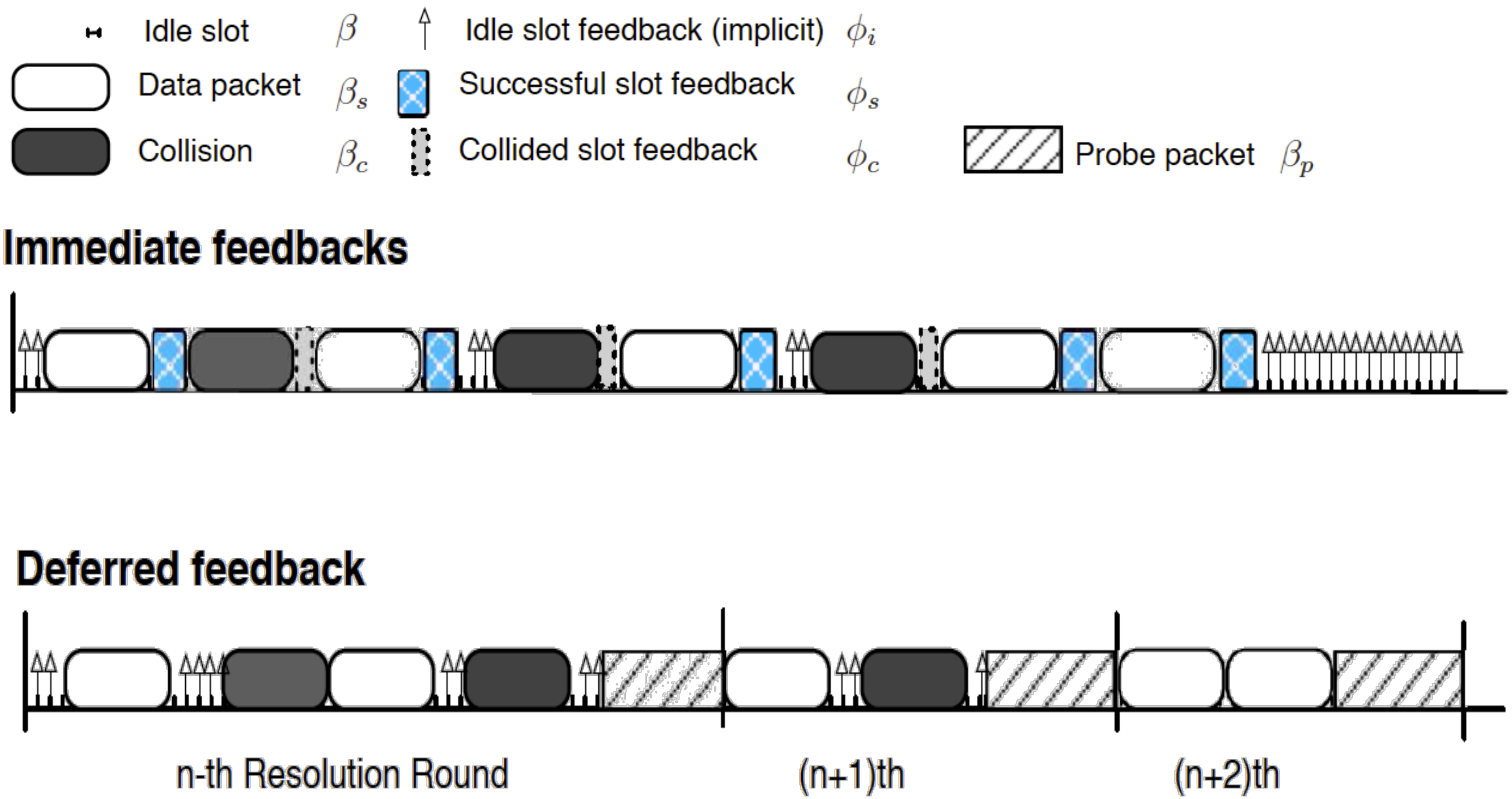
The cost of neglecting feedback cost…



The larger the ACK tx time (ϕ_s) the lower the asymptotic throughput of immediate-feedback BRAs

A different approach: deferred feedback strategies



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Classical Dynamic Framed Slotted Aloha

- Framed Slotted ALOHA (FSA)
  - Slots are organized in frames of W slots
  - In each frame, nodes transmit in random slots
  - Feedback is returned only at the end of the frame by using a *probe packet*
- Dynamic FSA
  - Frame size is adjusted dynamically to maximize the expected <u>*per-frame*</u> throughput
- Drawback: probing cost is neglected!
  - Maximizing per-frame throughput does not necessarily minimize the overall batch resolution interval

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Our proposal

- ABRADE: Adaptive Batch Resolution Algorithm with Deferred Feedback
  - Basically a dynamic framed slotted ALOHA with a novel frame-adaptation strategy that keeps into account all costs!
  - Batch size *n* is assumed to be known beforehand!
- ABRADE+: couple ABRADE with a batch size estimate algorithm
  - No prior knowledge about the batch size

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ABRADE in a nutshell

- Assumption: the (residual) batch size "n" is known
- The frame size w_n of the next round is selected in order to minimize the overall Batch Resolution Interval (BRI) for that batch

number of successful collided idle slots in the frame

$$T(n) = \mathrm{E}\Big[\underbrace{s + c + i\tau + b_p}_{\text{Frame duration}} + \underbrace{T(n-s)}_{\text{Residual batch resolution interval}} \Big| w, n\Big]$$

BRI for batch of size n

Frame Size

Batch Size

w*$_n$: optimal frame length for a batch of size n

$p_{w,n}(s) = \Pr[s|w,n]$

$$w_n^* = \arg\min_w \left\{ \frac{\beta_p + w\beta_c + n(1-\beta_c)\left(1-\frac{1}{w}\right)^{n-1} + w\left(1-\frac{1}{w}\right)^{n}(\beta-\beta_c) + \sum_{s=1}^{\infty} T^*(n-s)\,p_{w,n}(s)}{1-p_{w,n}(0)} \right\}$$

Dynamic programming optimization

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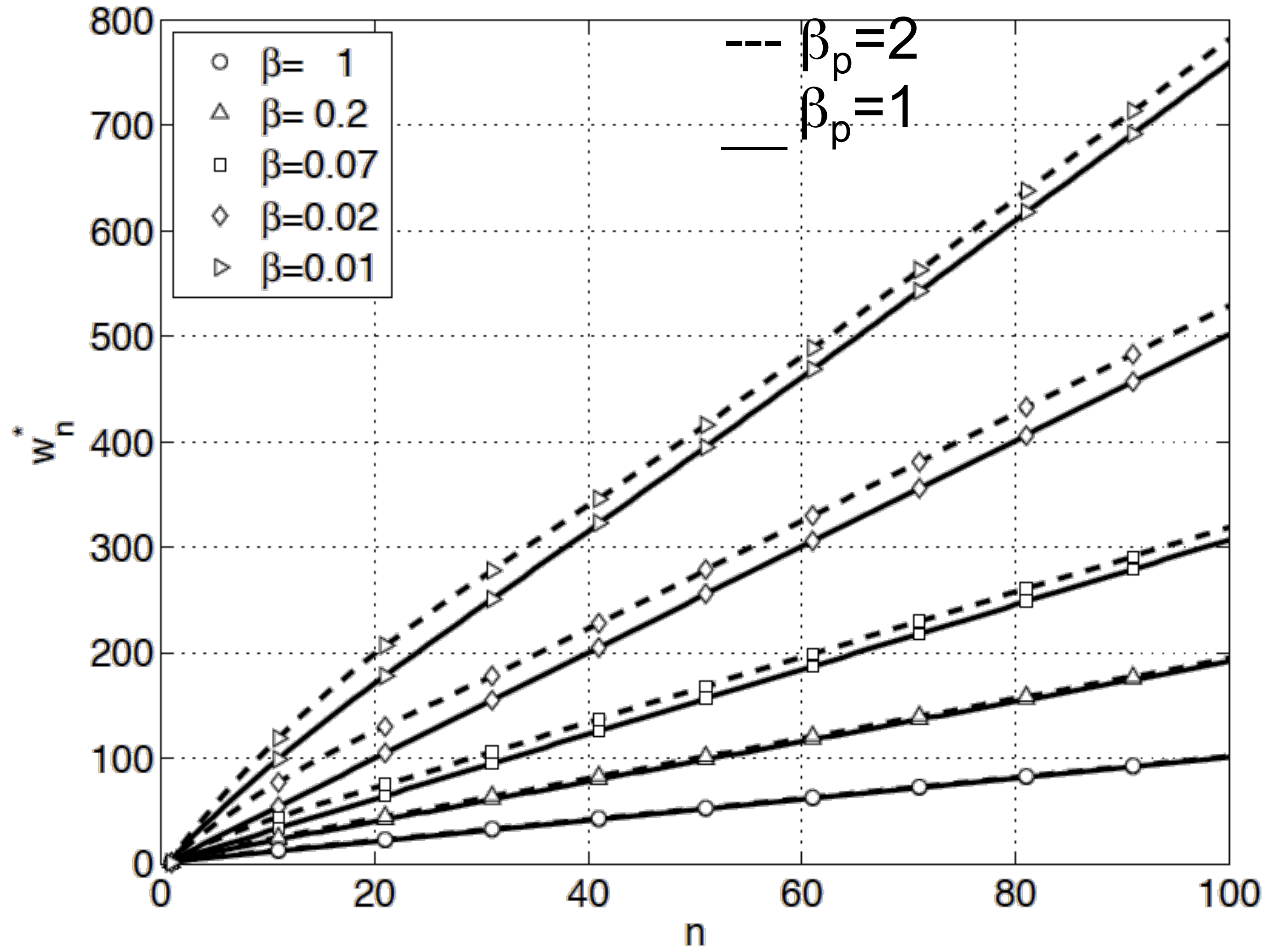
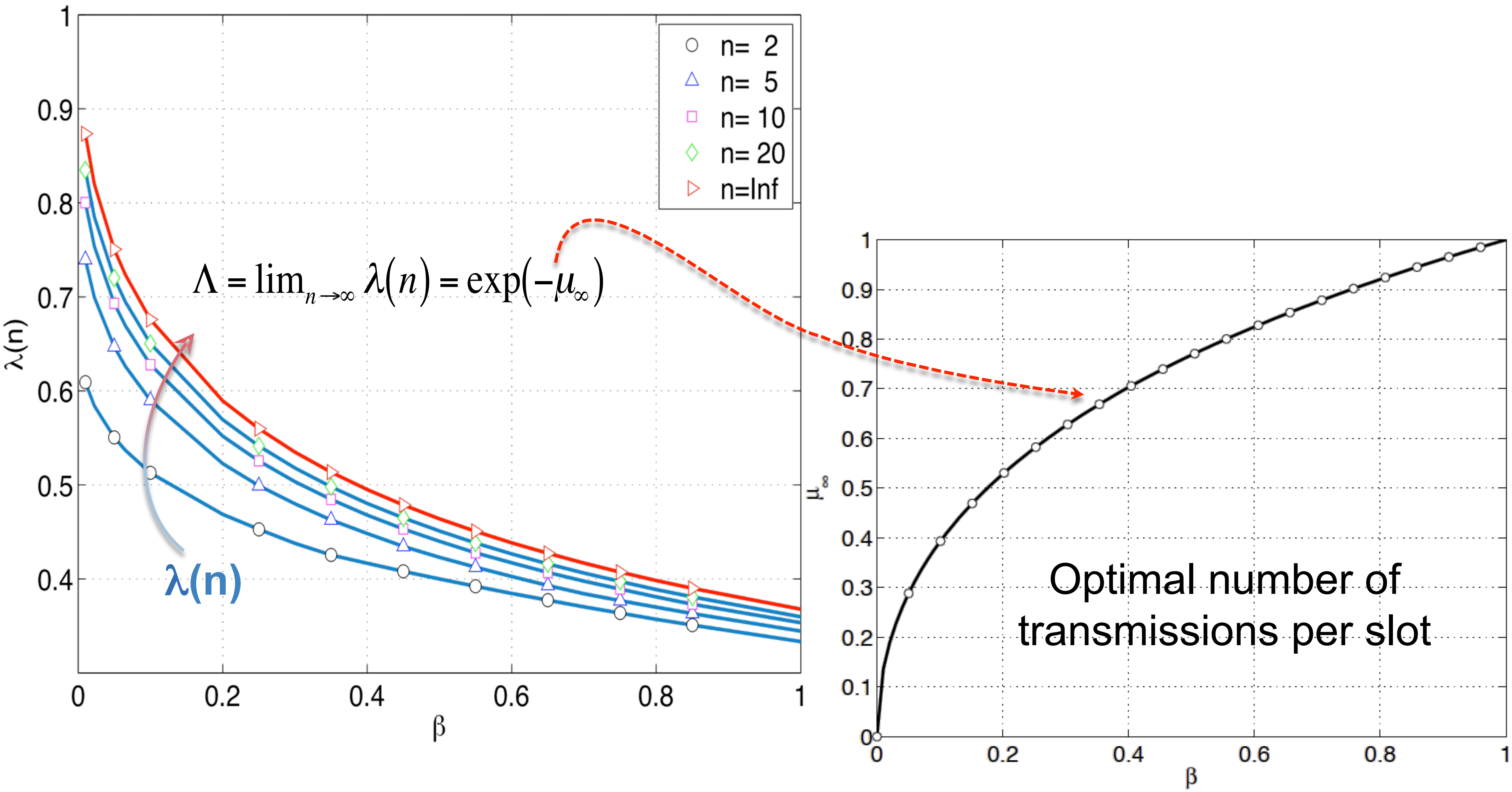
Optimal frame length



ABRADE's throughput



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ABRADE+: batch size estimate

- ABRADE needs prior knowledge of the batch size *n*
- In most cases, *n* is unknown and needs to be estimated
- Estimate can be refined as the batch resolution proceeds
- ABRADE+ is as ABRADE with two add-ons
  1. Batch Size Estimate Function (BSEF)
  2. Start up phase

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Quick survey of most-known BSEFs

- V=<s,c,i> → $\hat{\text{n}}$ estimate of *n*
  - [Schoute83]: $\hat{\text{n}} = \text{s} + 2\text{c}$
  - [Cha&Kim05]: $\hat{\text{n}} = \text{s} + 2.39\text{c}$
  - [Vogt02]: $\hat{\text{n}} = \arg\min_{\text{n}} \left\{ \left(s - \text{E}[s|n]\right)^2 + \left(c - \text{E}[c|n]\right)^2 + \left(i - \text{E}[i|n]\right)^2 \right\}$
  - [Khandelwat06]: $\hat{\text{n}} = \arg\min_{\text{n}} \left\{ \left(s - \text{E}[s|n]\right)^2 \right\}$ $\hat{\text{n}} = \arg\min_{\text{n}} \left\{ \left(i - \text{E}[i|n]\right)^2 \right\}$
  - [Kodialam06]: $\hat{\text{n}} = w \log\left(\frac{1}{i}\right)$ $\hat{\text{n}} = \left\{ w\mu : (1+\mu)e^{-\mu} = \frac{w-c}{w} \right\}$
  - [Zanella12]: $\hat{\text{n}} = \left\{ w\mu : \frac{\mu w - s}{c} = \frac{\mu\left(e^{\mu} - 1\right)}{e^{\mu} - 1 - \mu} \right\}$

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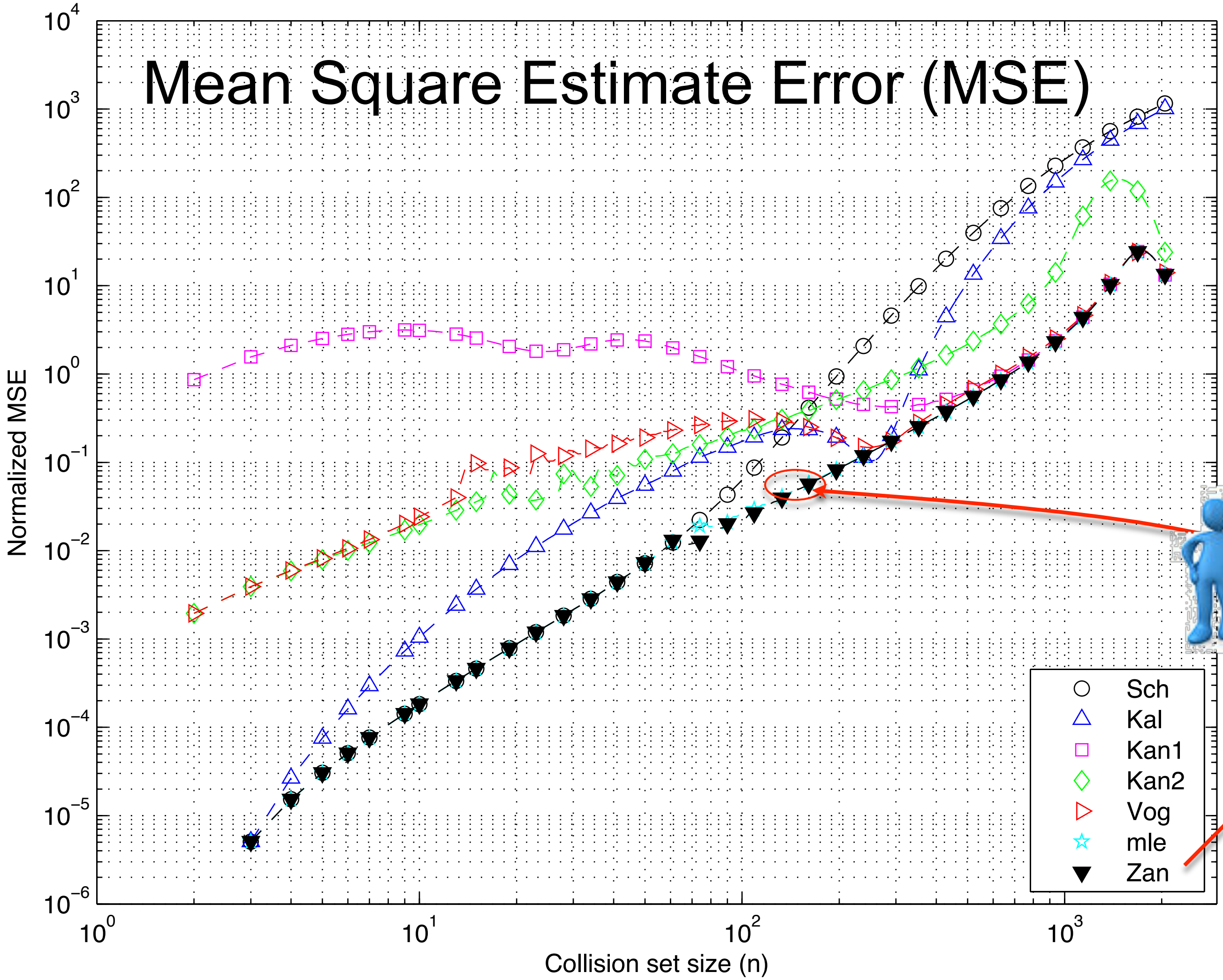
A glance at BSEFs performance



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Start up phase

- What frame size w_0 shall be used at the very fist cycle?
  - w_0 shall be small, to have a first estimate of *n* as soon as possible
  - w_0 shall be large to avoid many collisions
- Solution: *Probabilistic* Framed Slotted Aloha
  - Nodes transmit with probability *p*
- Issue: p, w_0 shall be set to strike a balance between estimate accuracy & performance loss

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Setting *p* and w_0

- Let m_n be the mean batch size *n*
  - if unknown, arbitrarily assumed equal to $N_{max}/2$
- Set *p* such that w_0 is optimal for a batch size equal to pm_n:

$$\frac{pm_n}{w_0} = \mu_\infty \rightarrow p = \frac{w_0}{m_n}\mu_\infty$$

- Set w_0 such that the mean square estimate error, MSE(p) is lower than Δm_n, where Δ is a design parameter

$$w_0 = \min\left\{ w : \mathrm{E}\left[\left(n - \frac{\hat{n}}{p} \right)^2 \middle| w \right] \leq \Delta m_n \right\}$$

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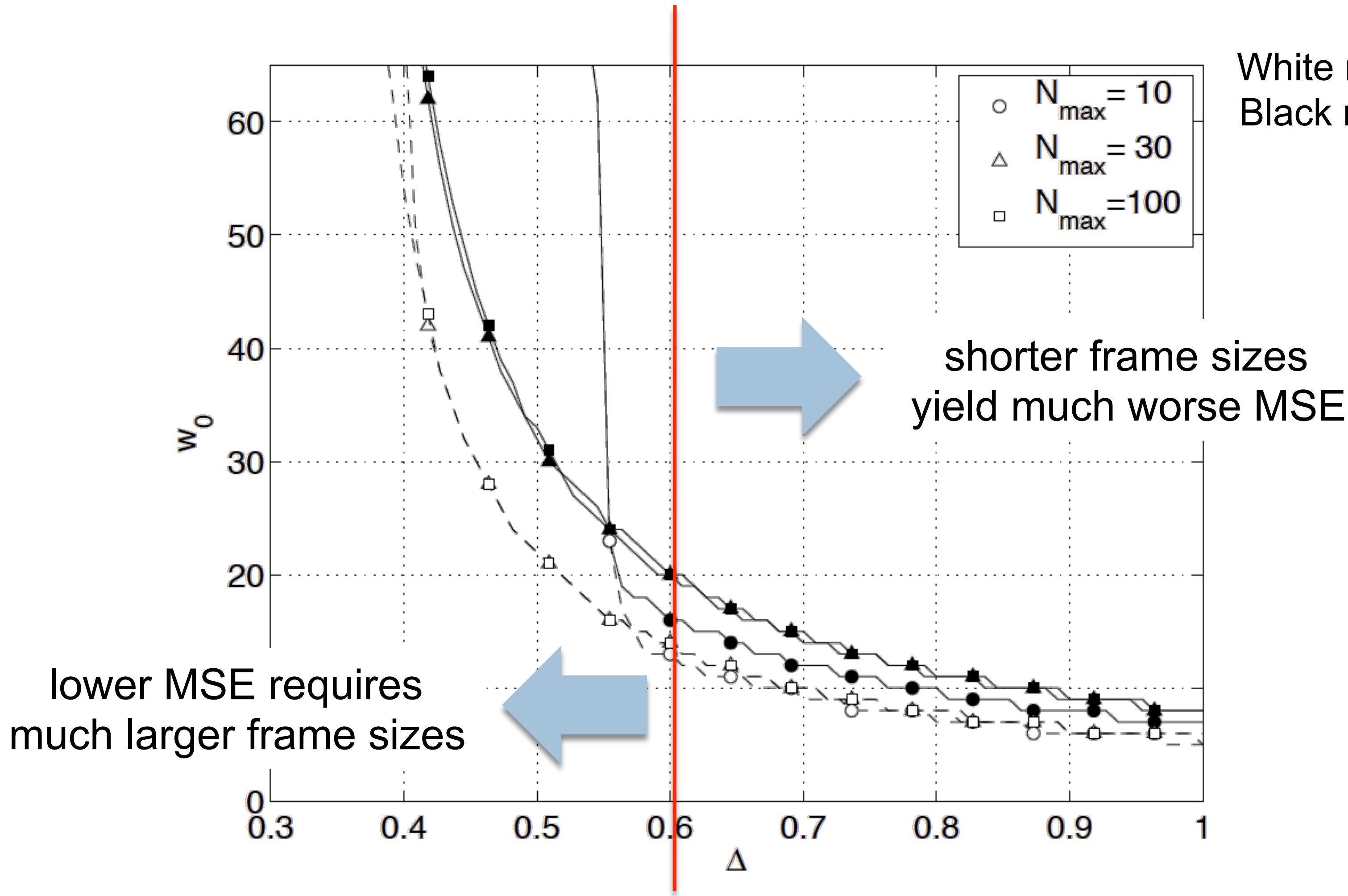
Initial frame size vs Δ

White marker: β=0.0654
Black marker: β=0.0225



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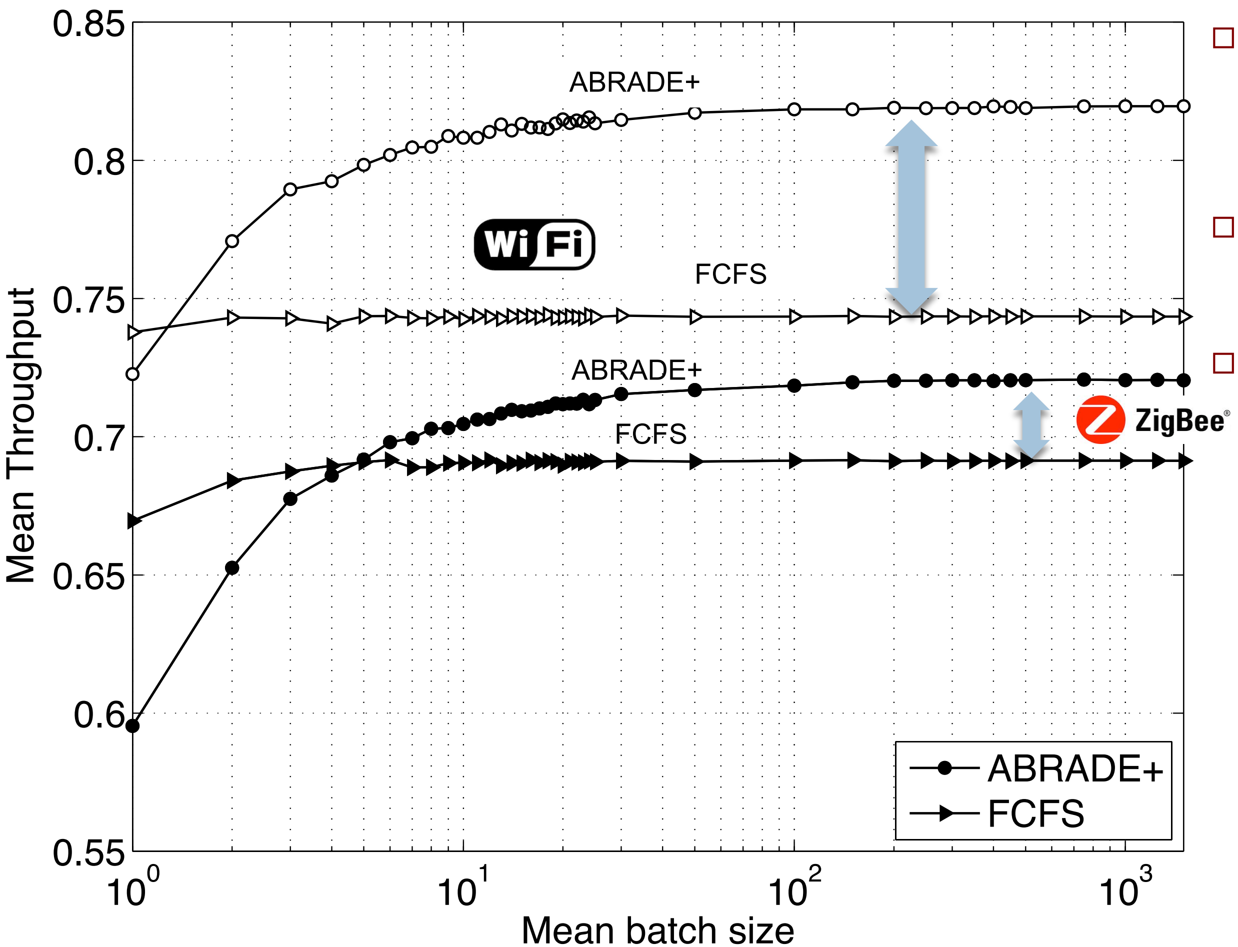
Case study

- Parameters set according to WiFi (WF) & ZigBee (ZB) specifications

1. Batch size *n* with Poisson distribution of known mean N
2. Batch size totally unknown to the algorithm
   - m_n arbitrarily set to 100
   - Δ=0.6

	T_{data} [ms]	b	b_s	b_c	$b_p=w/L_{max}$
WiFi	0.399	0.0225	0.1319	0.1319	w/18496
ZigBee	4.896	0.0654	0.1111	0.0458	w/944

1. Poisson: Throughput



- Asymptotic throughput gain of ~9% for WF and ~6% for ZB
- Performance crossing for batches of small size
- Slightly worse for extremly small batches
  - Pay the cost of long probe message

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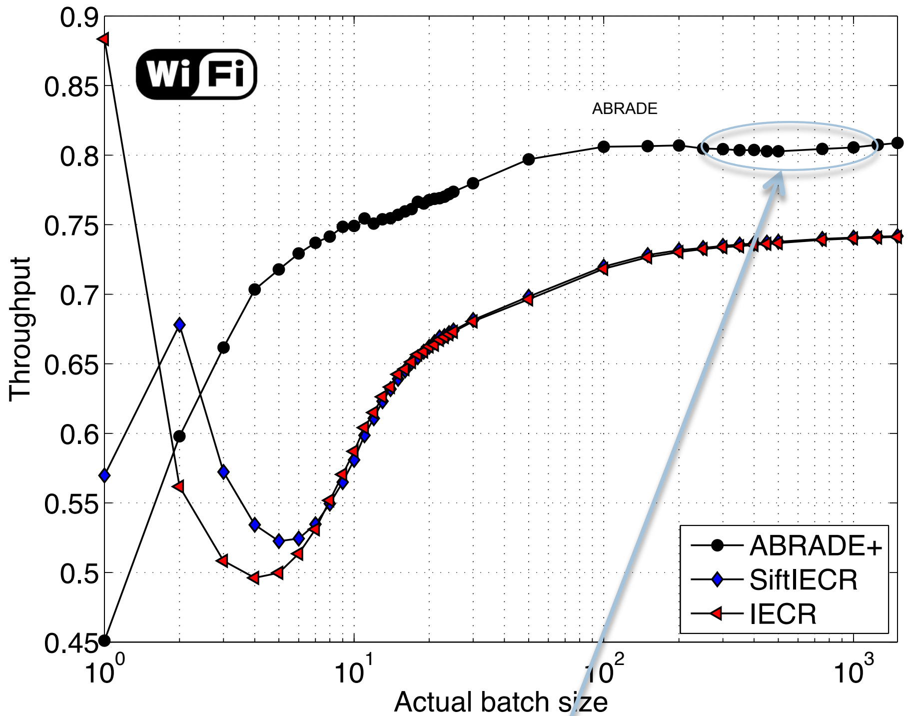
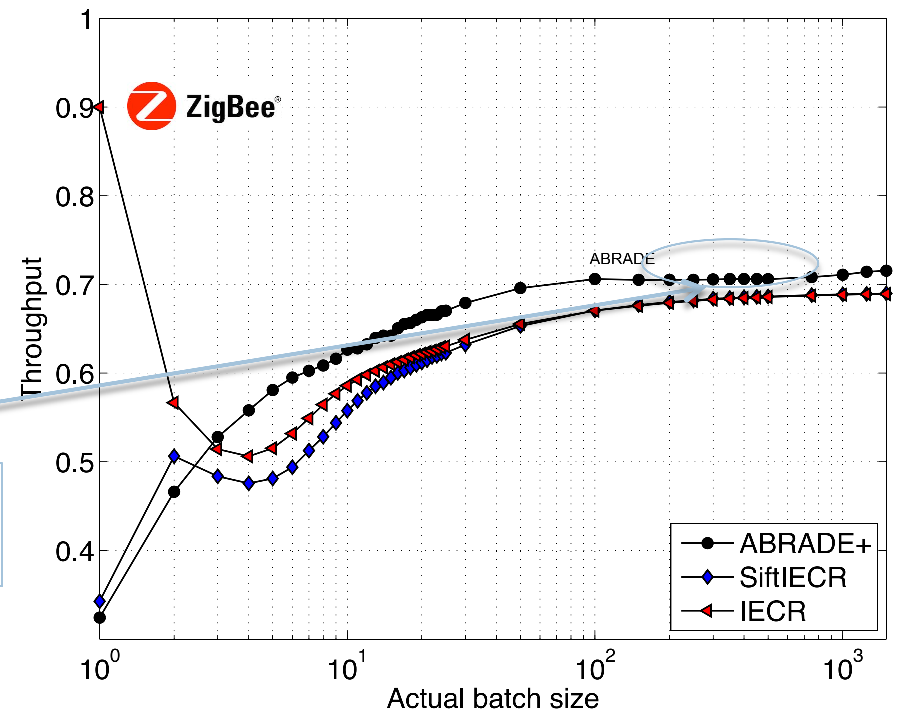
2. Unknown: Throughput



- Throughput gain is maintained also in the case of unknown batch size, as long as the batch is larger than few units
- Gain is more evident for WF than ZB



Perfomance contraction due to initial parameter setting (m_n=50)

Summarizing

- The batch resolution problem is still challenging
  - Count and identify RFtags
  - Bunch of sensors replying to probes
- Analysis shall carefully consider all protocol layer aspects
  - Initialization & feedback may have dramatic impact
- Large literature, but still much to be done!

Main bibliography

- J. Capetanakis, "Tree algorithms for packet broadcast channels," IEEE Trans. on Information Theory, vol. 25, no. 5, pp. 505–515, Sep. 1979.
- R. Gallager, "Conflict resolution in random access broadcast networks," in AFOSR Workshop Commun. Theory Appl., Sep. 1978, pp. 74–76.
- Zanella, A., "Adaptive Batch Resolution Algorithm with Deferred Feedback for Wireless Systems," Wireless Communications, IEEE Transactions on , vol. 11, no.10, pp.3528,3539, October 2012
- A. Zanella "Estimating Collision Set Size in Framed Slotted Aloha Wireless Networks and RFID Systems". IEEE Communications Letters, Volume 16, Issue 3, pp: 300-303, March 2012

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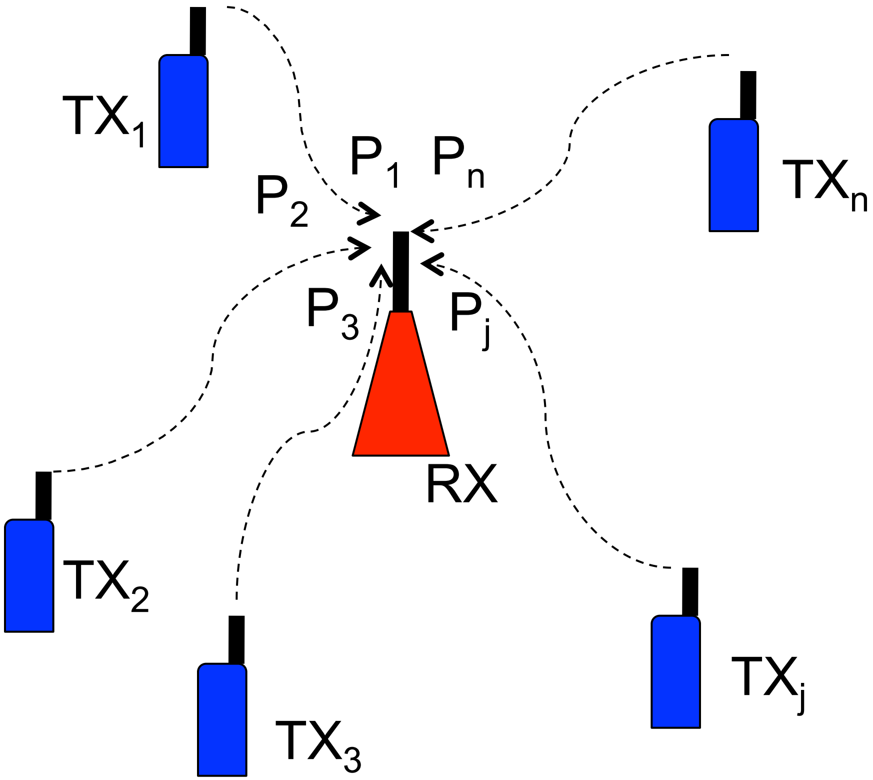
Improving M2M cell capacity

Exploiting multipacket reception capabilities and SIC

The problem

- Reference scenario:
  - one base station, multiple transmitters, uplink channel
- The problem:
  - How many transmitters can be served?
  - What's the maximum *cell capacity?*
  - How can we get it?



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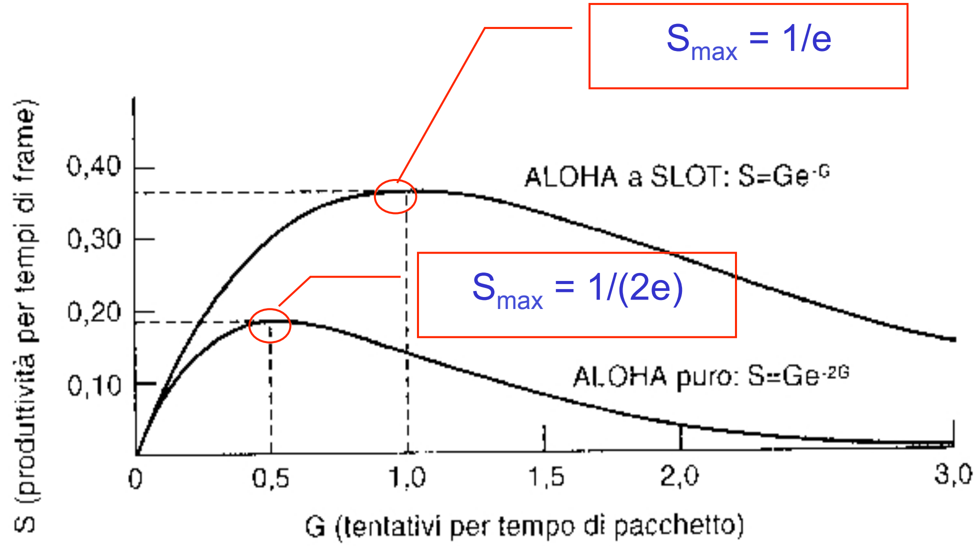
The literature

- Classic Aloha model [Kleinrock75]:
  - Destructive interference: one single transmission at a time
  - Max throughput: S = 1/(2e)
  - Slotted version: S = 1/e



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Capture

- **Capture phenomenon** [LauLeung, TCOM92]
  - When the various signals are received with **significantly different powers** → *capture effect* may take place
  - the strongest signals may survive the collision and be correctly decoded
- Generalization: "Capture" occurs when *one or more* of the overlapping signals are successfully decoded by the receiver despite the interference

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Capture models

- Statistical geometry model [Roberts, ComRev75]
  - Intended signal is captured when the **strongest interferer** is sufficiently far apart from the receiver
  - Doesn't account for actual signal propagation phenomena nor does it consider cumulative effect of multiple "weak" interferers
- Arrival Time model [Davis&Gronemeyer, TCOM80]
  - Intended signal is captured when arrival instants of the first and second signals are sufficiently apart
  - Doesn't account for signal strengths, nor for simultaneous transmissions

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Other capture models

- Counting model [Wieselthier et al, TCOM89]
  - Capture occurs with probability that depends on the number of overlapping signals
  - Doesn't account for actual signal powers
  - At most one capture per transmission attempt
- Power model [Ephremides&Luo, TIT02]
  - Capture if no other signal with higher power overlaps in time
  - Doesn't account for cumulative effect of multiple "weak" interferers

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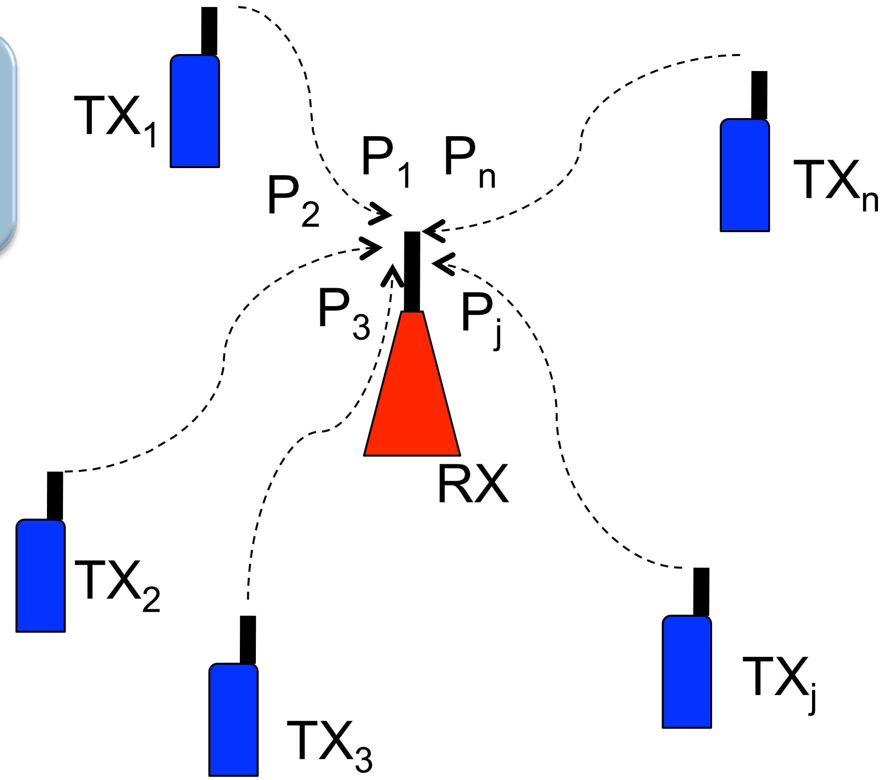
MPR and Stability

- MPR & Stability [Ghez, Verdu, Schwartz, ITAC88]
  - They assume a given pmd for the number *r* of captured signals out of a collision of *n* overlapping signals
  - Show that MPR can stabilize ALOHA and that max throughput is $S_{max} = E[r]$
  - Don't give an expression for the pmd of *r* given *n*

Physical capture model

Decoding model: SINR threshold

- Use of strong coding to achieve Shannon capacity
- P_j : power of the *j*-th signal at the receiver
- N_0: noise power (neglected)
- γ_j : SINR of the *j*-th signal
- b : capture threshold



Aggregate interference

$$\gamma_j = \frac{P_j}{I + \cancel{N_0}}$$

γ_j > b ➔ *j*-th signal is correctly decoded (capture)

γ_j < b ➔ *j*-th signal is collided (missed)

Multi Packet Reception

- MPR can be enabled by means of
  - *Signal spreading* (DSSS)
    - $b<1$ → multiple signals (up to $1/b$) can be captured at a time
  - *Successive interference cancellation* (SIC)
    1. Capture signal *j* with SINR $\gamma_j > b$
    2. Reconstruct and cancel signal *j* from the overall received signal
       - Cancellation leaves a fraction ***z*** of residual interference power
    3. Repeat iteratively

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Open questions

System parameters

- Number of simultaneous transmissions (*n*)
- Statistical distribution of the receiver signal powers (P_i)
- Capture threshold (*b*)
- Max number of SIC iterations (*K*)
- Interference cancellation ratio (*z*)

Capture probability?

System throughput?

The answer

- Capture probability
  - $C_n(r;K)$=Pr[*r* signals out of *n* are captured within *at most K* SIC cycles]
- Computing $C_n(r;K)$ is difficult because the **SINRs** are all **coupled!!!**
  - E.g. $\gamma_1 = \frac{P_1}{P_2} > b \Rightarrow \gamma_2 = \frac{P_2}{P_1} < \frac{1}{b}$
  - Computation of $C_n(r;k)$ becomes more and more complex as the number *n* of signals increases
- SIC makes things even worse

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State of the art

- **Narrowband (b>1), No SIC (K=0)**
  - [Zorzi&Rao,JSAC1994,TVT1997] derive the probability $\mathbf{C_n(1;0)}$ that **one signal** is captured
    - MPR and SIC are not considered
- **Wideband (b<1), No SIC (K=0)**
  - Can capture multiple signals in one reception cycle
  - [Nguyen&Ephremides&Wieselthier,ISIT06, ISIT07] derive the probability $\mathbf{1-C_n(0;0)}$ that **at least one signal** is captured
    - Expression involves n folded integrals, does not scale with *n*
- **Wideband (b<1)+SIC (K>0)**
  - [ViterbiJSAC90] shows that SIC can achieve Shannon capacity in AWGN channels
    - Requires suitable received signals power allocation
  - [Narasimhan, ISIT07] studies outage rate regions in presence of Rayleigh fading
    - Eqs can be computed only for few users
  - [Weber et al, TIT07] study SIC in ad hoc wireless networks
    - Derive **bounds** on the transmission capacity based on stochastic geometry arguments

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State of the art

- **Wideband (b<1) + SIC (K>0) (cont)**
  - [ZanellaZorzi, TCOM2012] provide a scalable method for the numerical evaluation of the capture probability distribution Cn(r;K)
    - Investigate capture distribution & system throughput when varying system parameters {n,b,K,z}
  - Provide approximate expressions for the capture probability and the MPR throughput

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SIGNET

CAPTURE PROBABILITY FOR PURE MPR CASE

No SIC (K=0)

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Problem statement

- The capture condition can be expressed as

$$\gamma_j = \frac{P_j}{\Lambda - P_j} > b \Rightarrow P_j > b(\Lambda - P_j) \Rightarrow \boxed{P_j > \Lambda \frac{b}{b+1} = \Lambda b'}$$

  - b' is termed *modified capture threshold*
  - b'Λ is named *absolute capture threshold*

- We aim at determining the expression of

$C_n(r)$=Pr[*r* signals out of *n* are captured]

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Capture distribution

- Because of the problem symmetry we have

$$C_n(r) = \binom{n}{r} \underbrace{\Pr(\overbrace{P_{1:r} > \Lambda b'}^{\text{r captured signals}}, \overbrace{P_{r+1:n} \le \Lambda b'}^{\text{n-r missed signals}})}_{c_n(r)}$$

Conditioning on Λ=x we get…

$$c_n(r) = \int_0^\infty \Pr\left(P_{1:r} > xb', P_{r+1:n} \le xb' \middle| \Lambda = x\right) f_\Lambda(x)\,dx$$

and applying Bayes' rule: P[A|B]P[B] = P[B|A]P[A]

$$c_n(r) = \int_0^\infty f\left(\Lambda = x \middle| P_{1:r} > xb', P_{r+1:n} \le xb'\right) \underbrace{\Pr\left(P_{1:r} > xb', P_{r+1:n} \le xb'\right)}_{\text{iid}\ \Downarrow\ \left(1 - F_P(xb')\right)^r F_P(xb')^{n-r}} dx$$

Conditioned aggregate received power Λ_r

- The issue is now to compute the PDF

$$f_{\Lambda_r}(x) = \Pr\left(\Lambda \cong x \middle| P_{1:r} > xb', P_{r+1:n} \le xb'\right)$$

- We introduce the auxiliary r.v.

$$\tilde{\Lambda}_r(u) = \sum_{h=1}^{r} \alpha_h(u) + \sum_{k=1}^{n-r} \beta_k(u)$$

iid rvs with PDF
$f_{\alpha(u)}(x)=f_P(x|P>u)$

iid rvs with PDF
$f_{\beta(u)}(x)=f_P(x|P\le u)$

- $\tilde{\Lambda}_r(u)$ gives the aggregate power **given that** r signals are above **u,** and n−r are below **u**➔ setting **u=xb'** we get

$$\boxed{f_{\Lambda_r}(x) = f_{\tilde{\Lambda}_r(xb')}(x)}$$

Auxiliary random variable

- Since $\alpha_h(u)$ and $\beta_h(u)$ are independent, we get

$$f_{\tilde{\Lambda}_r(u)}(x) = \left(\overbrace{f_{\alpha(u)} \otimes f_{\alpha(u)} \otimes \cdots \otimes f_{\alpha(u)} \otimes f_{\beta(u)} \otimes f_{\beta(u)} \otimes \cdots \otimes f_{\beta(u)}}\right)(x)$$

Fourier Transform

$$f_{\tilde{\Lambda}_r(u)}(x) = \underbrace{\int_{-\infty}^{+\infty} \left[\Psi_{a(u)}(\xi)\right]^r \left[\Psi_{\beta(u)}(\xi)\right]^{n-r} e^{j2\pi x\xi}\, d\xi}_{\text{Inverse Fourier Transform}}$$

- Putting all the pieces together we get the final expression

$$C_n(r) = \binom{n}{r} \int_0^{\infty} \left(1 - F_P(xb')\right)^r F_P(xb')^{n-r} \times$$

$$\left(\int_{-\infty}^{+\infty} \left[\Psi_{a(xb')}(\xi)\right]^r \left[\Psi_{\beta(xb')}(\xi)\right]^{n-r} e^{j2\pi x\xi}\, d\xi\right) dx$$

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Capture distribution: approximate expression

- If n›› & r=0 or r=n or r≈n/2 the central limit theorem applies

$$\tilde{\Lambda}_r(u) = \sum_{h=1}^{r} \alpha_h(u) + \sum_{k=1}^{n-r} \beta_k(u)$$

$$N\left(r m_{\alpha(u)}, r\sigma^2_{\alpha(u)}\right) \qquad N\left((n-r) m_{\beta(u)}, (n-r)\sigma^2_{\beta(u)}\right)$$

- from which we get the following approximate expression of $C_n(r)$:

$$\tilde{C}_n(r) = \binom{n}{r} \int_{nP_m}^{nP_M} \frac{\exp\left(-\frac{\left(x - r m_{\alpha(xb')} - (n-r)\, m_{\beta(xb')}\right)^2}{2\left(r\sigma^2_{\alpha(xb')} + (n-r)\sigma^2_{\beta(xb')}\right)}\right)}{\sqrt{2\pi\left[r\sigma^2_{\alpha(xb')} + (n-r)\sigma^2_{\beta(xb')}\right]}} \times (1 - F_P(b'x)^r) F_P(b'x)^{n-r} dx$$

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Throughput

- k: reception capability
  - max number of signals that can be simultaneously decoded
- $S_n(k)$: average number of signals captured by a system with reception capacity k and a collision size n

$$S_n(k) = \sum_{r=1}^{k-1} r\, C_n(r) + k \sum_{r=k}^{n} C_n(r)$$

- Note: previous literature focused on $S_n(1)=1-C_n(0)$ only!

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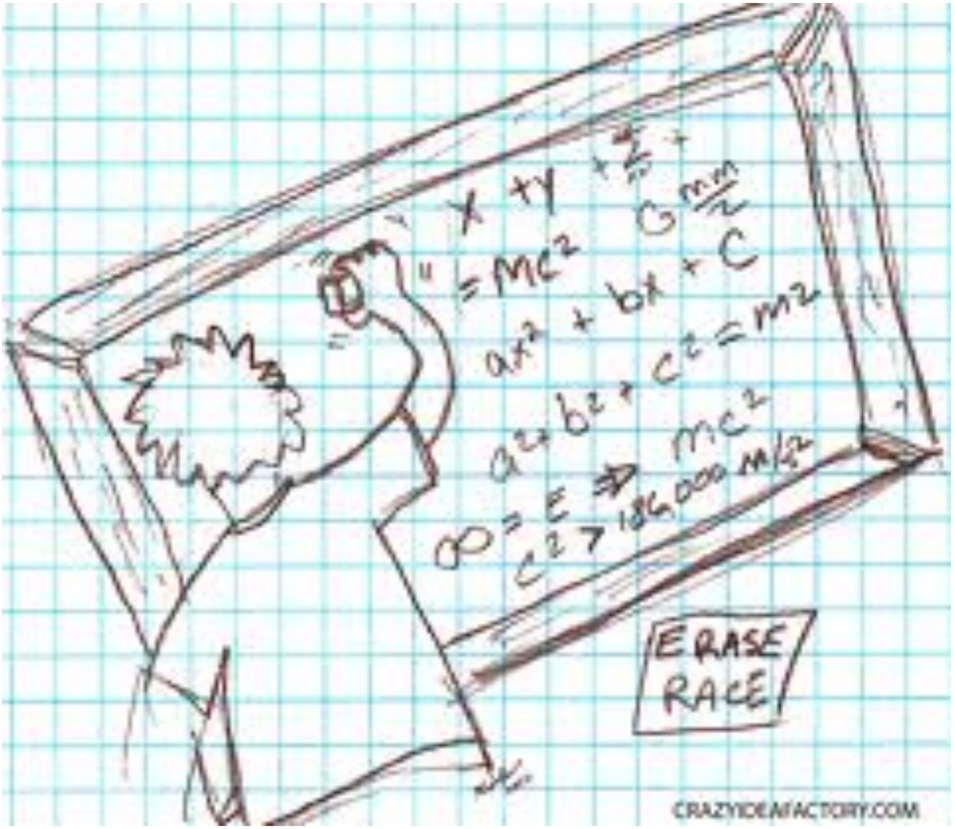
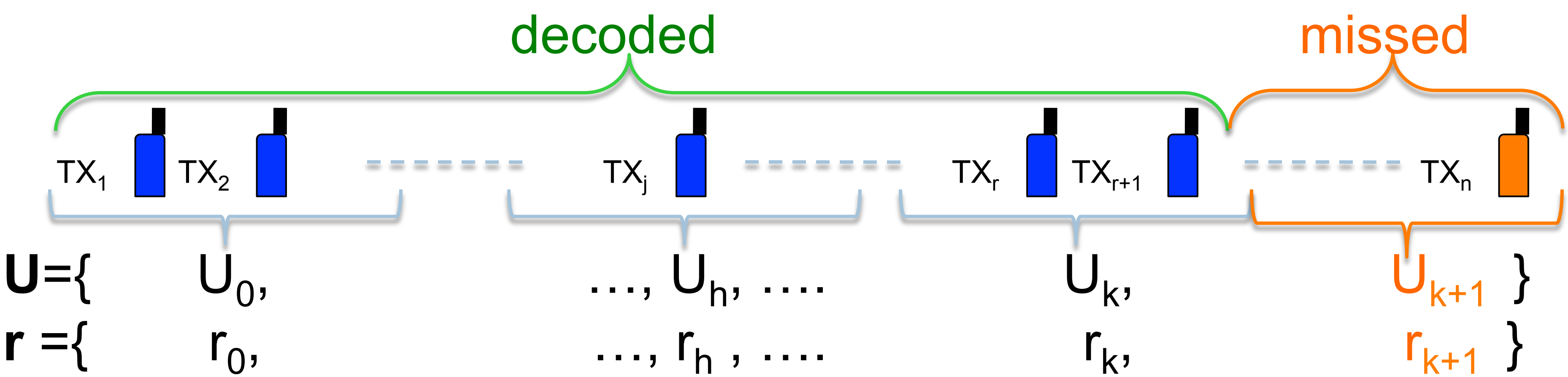


SIGNET

ANALYSIS OF THE SIC CASE

Notation: reception set and vector

- n : number of overlapping signals
- r : overall number of decoded signals
- h ={0,1,…,K}: SIC iteration
- U_h: set of signals decoded at the *h*-th SIC iteration
  - U_{k+1}: set of missed signals at the end of the reception process
- **r**=$[r_0,r_1,\ldots,r_k,r_{k+1}]$: reception vector
  - $r_h=|U_h|$, $r_{k+1}=|U_{k+1}|= n-r$



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Notation: aggregate power

- Set of signal powers for users in U_h

$$\mathbf{P}_h = \left\{ P_{r_0+r_1+\ldots+r_{h-1}+1}, \ldots, P_{r_0+r_1+\ldots+r_h} \right\}$$

- Aggregate power of users in U_h

$$\boxed{\Gamma_h = \sum_{j \in U_h} P_j}$$

- Overall sign. power at the *h*-th decoding cycle

$$\boxed{\Lambda_h = z \sum_{j=0}^{h-1} \Gamma_j + \sum_{i=h}^{k+1} \Gamma_i}$$

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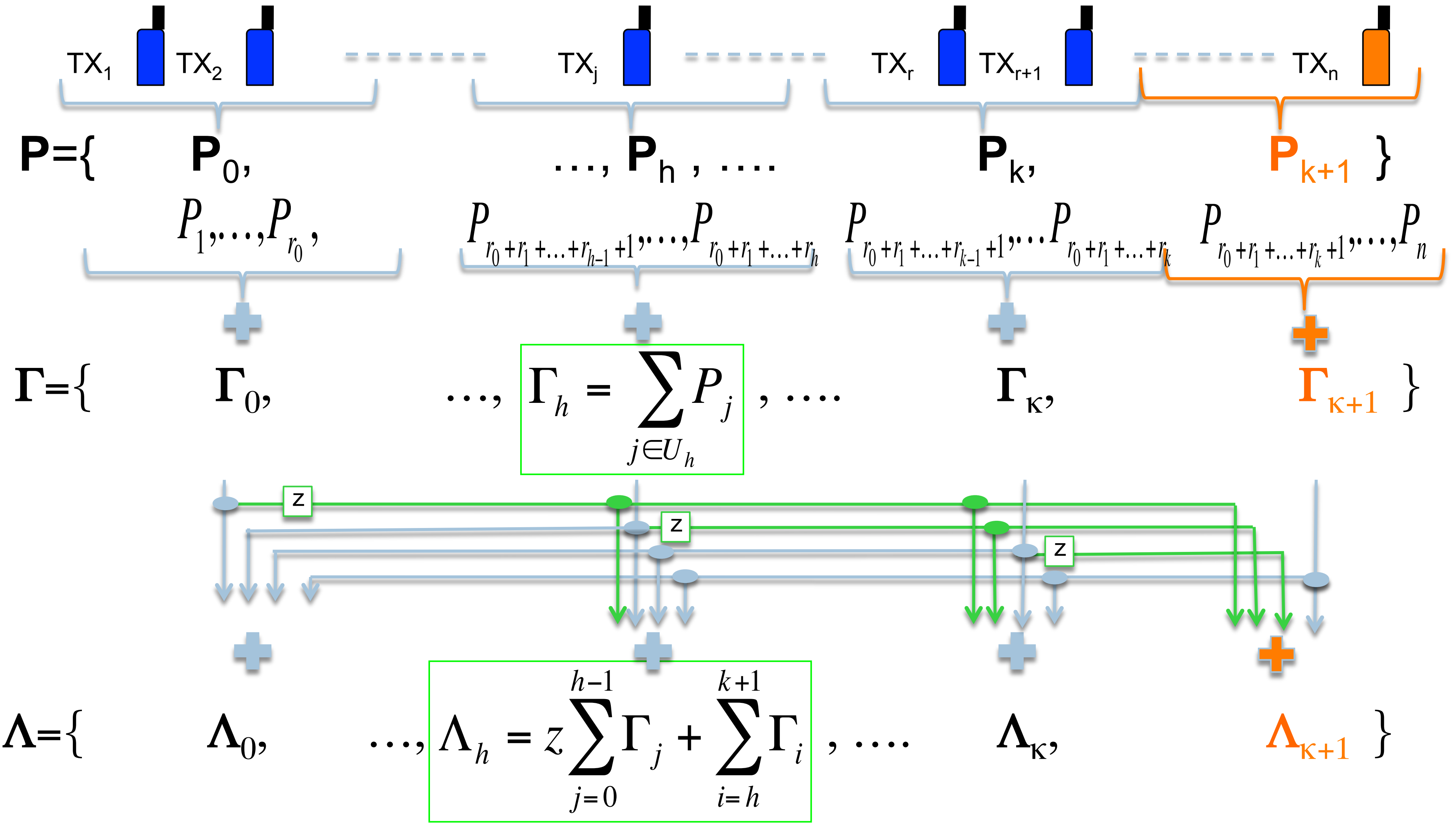
Visually



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Step 1: a bit of combinatorial analysis

$$\Pr\left[r \text{ signals are decoded in at most } K \text{ iterations}\right]$$

Combinatorial coefficient

$$\underbrace{C_n(r;K)} = \sum_{k=0}^{K} \sum_{\mathbf{r}} A(\mathbf{r}) \underbrace{c(\mathbf{r})}$$

Ordered probability distribution

$$\Pr\left[\begin{array}{c} \text{first } r_0 \text{ signals are decoded at iteration } 0 \\ \text{successive } r_1 \text{ signals are decoded at iteration } 1 \\ \vdots \\ \text{successive } r_h \text{ signals are decoded at iteration } h \\ \vdots \\ \text{last } r_{k+1} \text{ signals are undecoded after } k \text{ iterations} \end{array}\right]$$

Step 2: express decoding probability in terms of P_i

- Signals in U_h are decoded at the h-th SIC iteration if
  1. were not decoded at previous iterations
  2. verify capture condition after h SIC iterations
- Mathematically $\forall j \in U_h,$

1. $\gamma_j = \dfrac{P_j}{\Lambda_{h-1} - P_j} \leq b \Rightarrow P_j \leq b'\Lambda_{h-1}$

2. $\gamma_j = \dfrac{P_j}{\Lambda_h - P_j} > b \Rightarrow P_j > b'\Lambda_h$

where $b' = \dfrac{b}{b+1}$

- Considering all k SIC iterations…

$$c(\mathbf{r}) = \Pr\left[\mathbf{P}_0 > b'\Lambda_0 \geq \mathbf{P}_1 > b'\Lambda_1, \cdots, b'\Lambda_{k-1} \geq \mathbf{P}_k > b'\Lambda_k, \mathbf{P}_{k+1} \leq b'\Lambda_{k+1}\right]$$

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Step 3: let's start conditioning

- The capture threshold at each SIC iteration are

$$b'\Lambda_h = b'\left(z\sum_{j=0}^{h-1}\Gamma_j + \sum_{i=h}^{k+1}\Gamma_i \right)$$

Aggregate power of signals in Ui

- Conditioning on $\{\Gamma_h = g_h\}$ the capture thresholds becomes deterministic

$$\lambda_h(\mathbf{g}) = b'\left(z\sum_{j=0}^{h-1} g_j + \sum_{i=h}^{k+1} g_i \right)$$

- Then, we can write (we omit **g** in the argument of λ_h)

$$c(\mathbf{r}) = \underbrace{\iiint}_{\text{k+2 nested integrals}} \Pr\left[\mathbf{P}_0 > \lambda_0 \geq \mathbf{P}_1 > \lambda_1, \cdots, \lambda_{k-1} \geq \mathbf{P}_k > \lambda_k, \mathbf{P}_{k+1} \leq \lambda_{k+1} \middle| \Gamma = \mathbf{g}\right] \underbrace{\Pr\left[\Gamma \cong \mathbf{g}\right]}_{\text{PDF of the random vector } \Gamma \text{ evaluated in } \mathbf{g}=[g_0,\ldots,g_{k+1}]} d\mathbf{g}$$

Step 4: swap terms

- Applying Bayes rule we get

$$c(\mathbf{r}) = \iiint \Pr\left[\Gamma \cong \mathbf{g} \middle| \mathbf{P}_0 > \lambda_0 \geq \mathbf{P}_1 > \lambda_1, \cdots, \lambda_{k-1} \geq \mathbf{P}_k > \lambda_k, \mathbf{P}_{k+1} \leq \lambda_{k+1}\right]$$

$$\underbrace{\Pr\left[\mathbf{P}_0 > \lambda_0 \geq \mathbf{P}_1 > \lambda_1, \cdots, \lambda_{k-1} \geq \mathbf{P}_k > \lambda_k, \mathbf{P}_{k+1} \leq \lambda_{k+1}\right]}\, d\mathbf{g}$$

iid $\prod_{h=0}^{k}\left[F_P(\lambda_h) - F_P(\lambda_{h-1})\right]^{r_h}$

- The issue now is to compute this conditional probability

iid

$$\Pr\left[\Gamma \cong \mathbf{g} \middle| \mathbf{P}_h \in (\lambda_h, \lambda_{h-1}]_{h=0}^{k}, \mathbf{P}_{k+1} \leq \lambda_{k+1}\right] =$$

$\lambda_{-1} = -\infty$

$$\Pr\left[\Gamma_{k+1} \cong g_{k+1} \middle| \mathbf{P}_{k+1} \in (0, \lambda_{k+1}]\right] \prod_{h=0}^{k} \Pr\left[\Gamma_h \cong g_h \middle| \mathbf{P}_h \in (\lambda_h, \lambda_{h-1}]\right]$$

Step 5: aux variables help decoupling terms

- Each Γ_h is the aggregate power of the signals in U_h **given that** they are in the interval $(\lambda_{h-1},\lambda_h]$
- We then define

$$\tilde{\Gamma}_h(u,v) = \sum_{i=1}^{r_h} \alpha_{h,i}(u,v)$$

- where $\alpha_{h,i}(u,v)$ are iid with PDF $f_{\alpha(u,v)}(x) = f_P(x \mid P \in (u,v])$
- Hence, for any given **g**, we have

$$\Pr\left[\Gamma_h \cong g_h \middle| \mathbf{P}_h \in (\lambda_h,\lambda_{h-1}]\right] =$$

Fourier Transform

$$\Pr\left[\tilde{\Gamma}_h(\lambda_h,\lambda_{h-1}) \cong g_h\right] = \left[\bigotimes_{i=1}^{r_h} f_{\alpha(\lambda_h,\lambda_{h-1})}\right](g_h) = \int_{-\infty}^{+\infty} \left[\Psi_{\alpha(\lambda_h,\lambda_{h-1})}(\xi)\right]^{r_h} e^{i2\pi\xi g_h} d\xi$$

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Step 6: put all pieces together

$$c(\mathbf{r}) = \iiint F_P(\lambda_{k+1})^{r_{k+1}} \left[\prod_{h=0}^{k} \left[F_P(\lambda_h) - F_P(\lambda_{h-1}) \right]^{r_h} \right]$$

$$\left[\int_{-\infty}^{+\infty} \prod_{h=0}^{k} \left[\Psi_{\alpha(\lambda_h, \lambda_{h-1})}(\xi) \right]^{r_h} e^{i2\pi\xi g_h} d\xi \right] \int_{-\infty}^{+\infty} \Psi_{\alpha(0,\lambda_{k+1})}(\xi) e^{i2\pi\xi g_{k+1}} d\xi d\mathbf{g}$$

- Number of nested integrals grows linearly with number K of SIC iterations, not with *n*
  - Equation can be computed for large values of *n*, provided that the number of SIC iterations remains reasonable (5÷6)
- Central limit theorem can be invoked for sufficiently large r_h

$$\int_{-\infty}^{+\infty} \Psi_{\alpha(u,v)}(\xi)^r e^{i2\pi\xi g} d\xi \approx \exp\left(\frac{\left(g - r m_{\alpha(u,v)} \right)^2}{2r\sigma^2_{\alpha(u,v)}} \right) \Bigg/ \sqrt{2\pi r \sigma^2_{\alpha(u,v)}}$$

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Throughput

- $S_n(k)$: average number of signals captured by a system wit collision size n and at most K SIC iterations
- Exact expression:

$$S_n(K) = \sum_{r=1}^{K} r C_n(r;K)$$

- Approximate (iterative) expression

$$\tilde{S}_n(K) = \sum_{h=0}^{K} \tilde{r}_h$$

- Where $\tilde{r}_h$ is the approximate mean number of signals decoded at the *h*-th SIC iteration

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Approximate mean number of captures: first reception

- Iteration h=0: number of undecoded signals n_0=n
  - Compute capture threshold

$$I_0 = b(n-1)E[P] = b(n-1)m_{\alpha(0,\infty)}$$

  - Approximate capture condition

$$\Pr[P > I_0] = 1 - F_P(I_0)$$

  - Mean number of decoded signals

$$\tilde{r}_0 = n(1 - F_P(I_0))$$

  - Residual interference power

$$R_0 = z\tilde{r}_0 E[P | P > I_0] = z\tilde{r}_0 m_{\alpha(I_0,\infty)}$$

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Approximate mean number of captures: first reception

- Iteration h>0: number of undecoded signals: $n_h = n - \sum_{i=0}^{h-1} \tilde{r}_i$
  - Compute capture threshold

$$I_h = b\left(\overbrace{\sum_{i=0}^{h-1} R_i}^{\text{Residual interf.}} + \overbrace{(n_h - 1) E\left[P \middle| P \le I_{h-1}\right]}^{\text{Interf. from undecoded signals}} \right)$$

  - Approximate capture condition

$$\Pr\left[P > I_h \middle| P \le I_{h-1}\right] = 1 - F_{\alpha(0, I_{h-1})}(I_h)$$

  - Mean number of decoded signals

$$\tilde{r}_h = n_h \left(1 - F_{\alpha(0, I_{h-1})}(I_h)\right)$$

  - Residual interference power

$$R_h = z\tilde{r}_h E\left[P \middle| I_{h-1} \ge P > I_h\right] = z\tilde{r}_h m_{\alpha(I_h, I_{h-1})}$$

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SIGNET

CASE STUDY

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Case study

Pure Path Loss (PL)	• TXs uniformly distributed within a circle of radius R centered at RX
Rayleigh Fading (RF)	• TXs at equal distance from RX (or **long-term power control**) but signals affected by multi-path fading
PathLoss & Rayleigh fading (PLRF)	• TXs uniformly scattered around RX, within a disk of radius R with signals affected by independent Rayleigh fading
LogNormal (LN)	• TXs at equal distance from RX (or **short-term power control**) but nominal signals power affected by small Gaussian noise [dBm]

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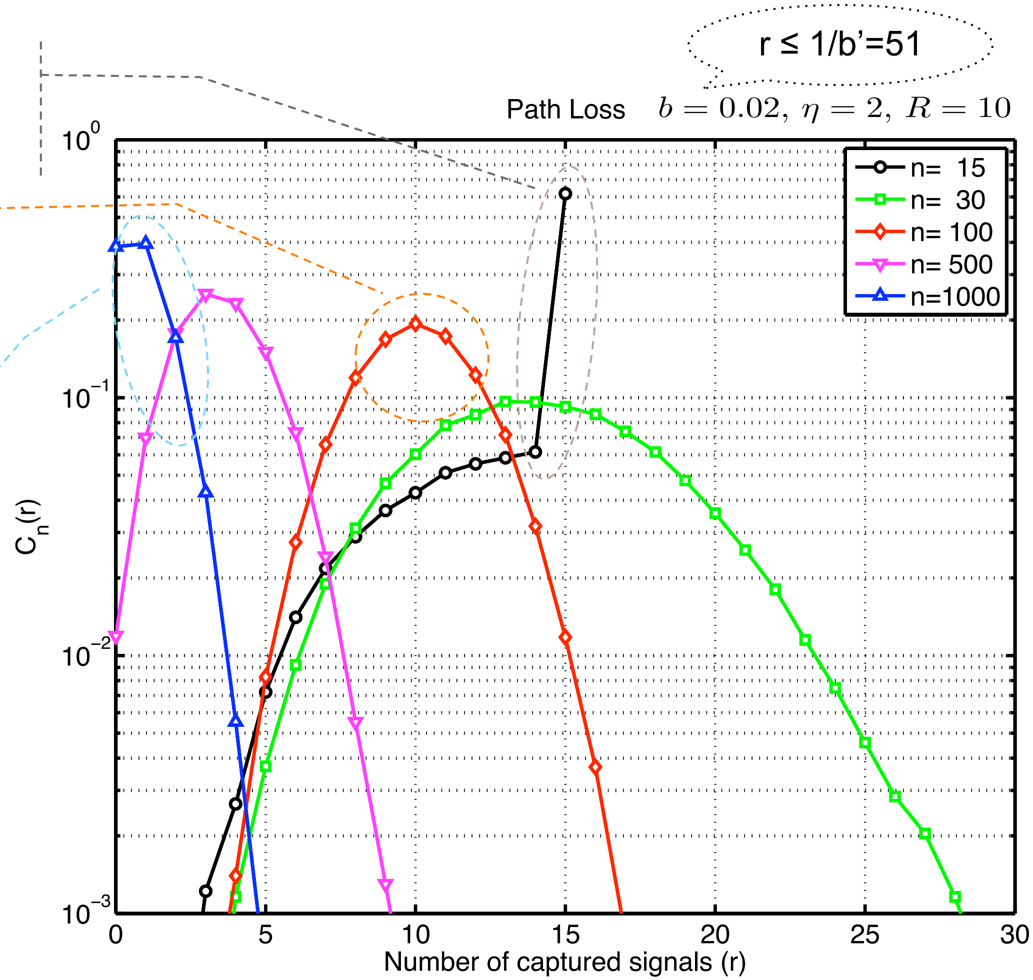
$C_n(r)$ in PL scenario

When n << 1/b', all signals are captured with high probability

When n > 1/b', the distribution of the number of signals captured is bell-shaped

When n >> 1/b', fewer and fewer signals are captured



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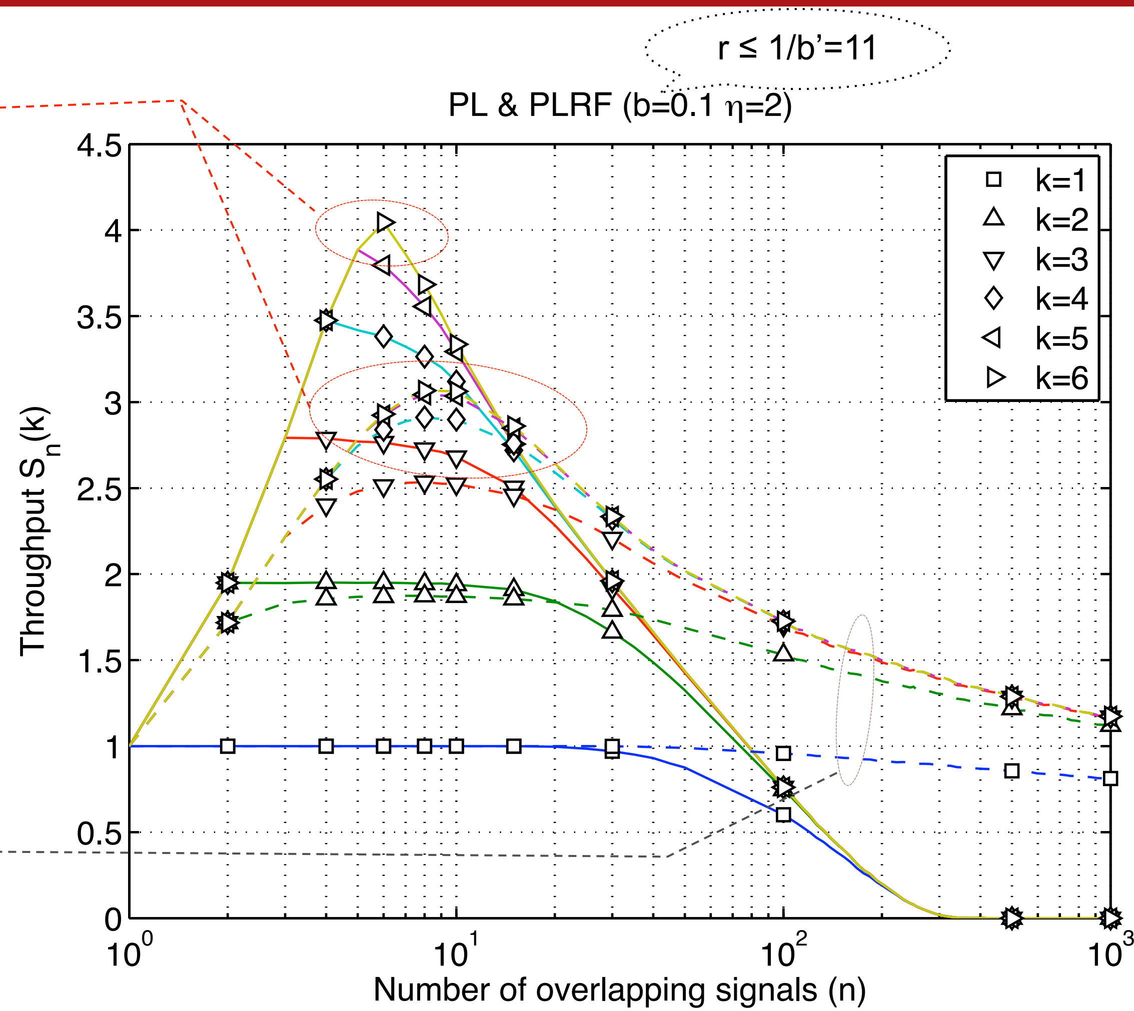
Throughput in PL & PLRF

S(6)≅S(11)

Max performance are closely approached even with partial reception capability.

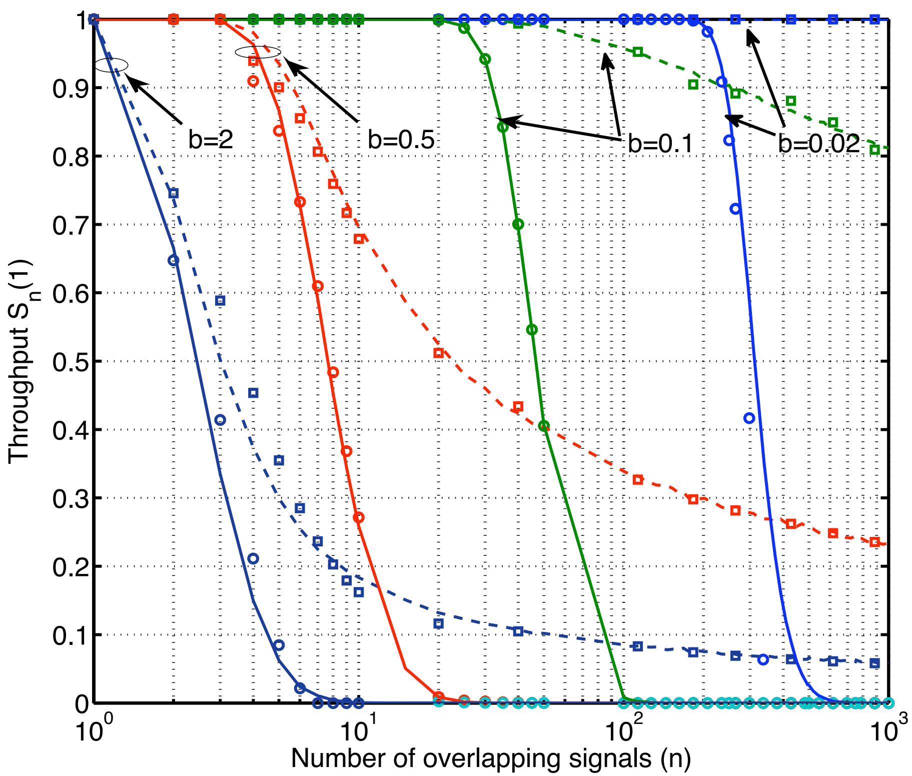
Rayleigh fading augments diversity of received signal strength & increases capture probabilities for large values of *n*



Approximate vs exact expressions

- $S_n(1)=1-C_n(0)$=Pr[capturing at least one signal]
  - metric considered in most of the previous literature
- The accuracy of the approx. of $C_n(0)$ is very good in all the considered cases
- The approximation of $C_n(r)$ is *not very good* when either r or n-r are positive but small (not shown here)

	RF	PLRF
Exact	———	- - - - - -
Approximate	◘	⊙



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SIGNET

PERFORMANCE WITH SIC

Rayleigh channel only

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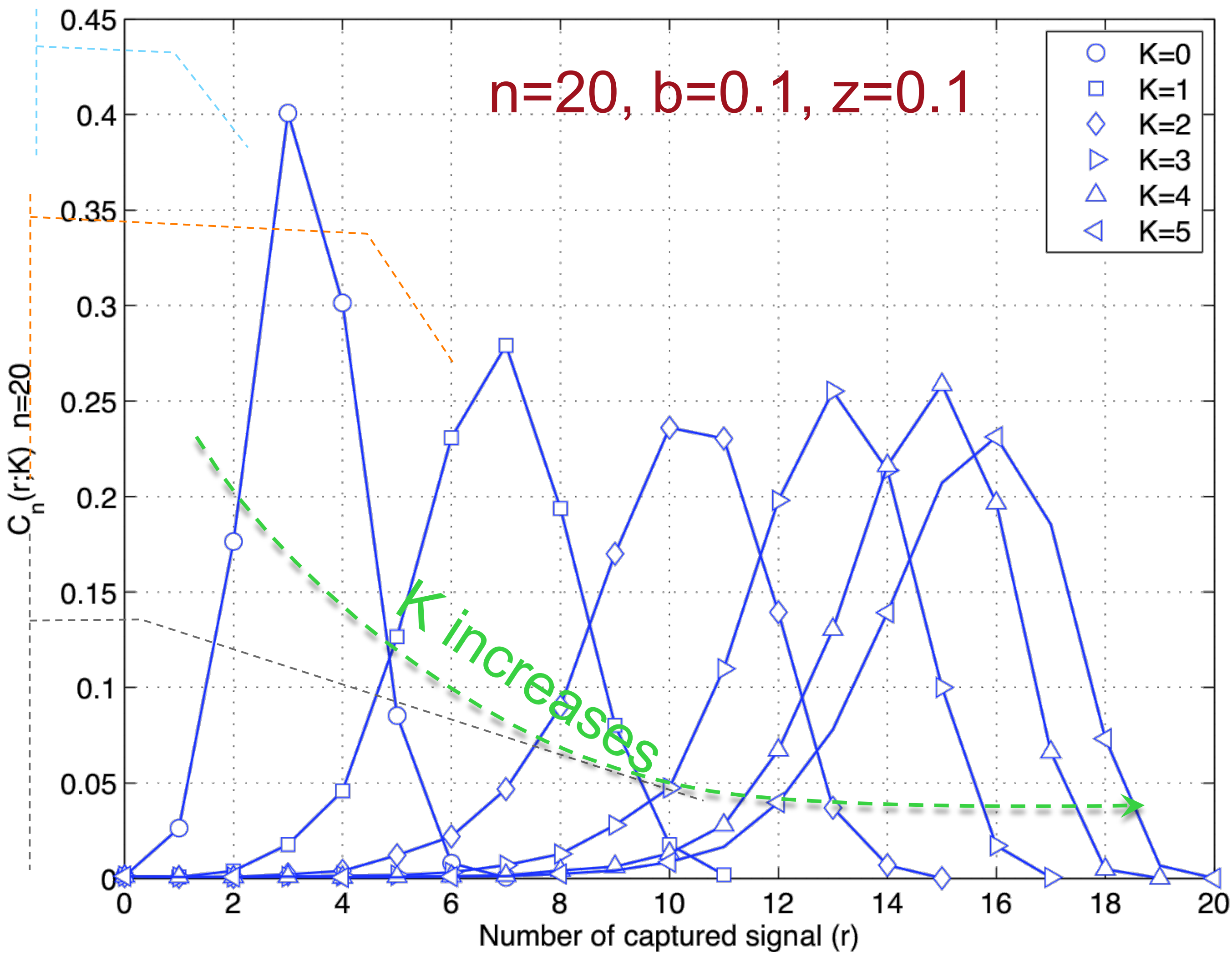
Capture probability distribution

No SIC (K=0): likely to decode 2÷5 signals

One SIC (K=1): likely to decode 4÷10 signals, double capture capabilities!!!

Multiple SIC (K>1): capture probability keeps improving, but gain reduces



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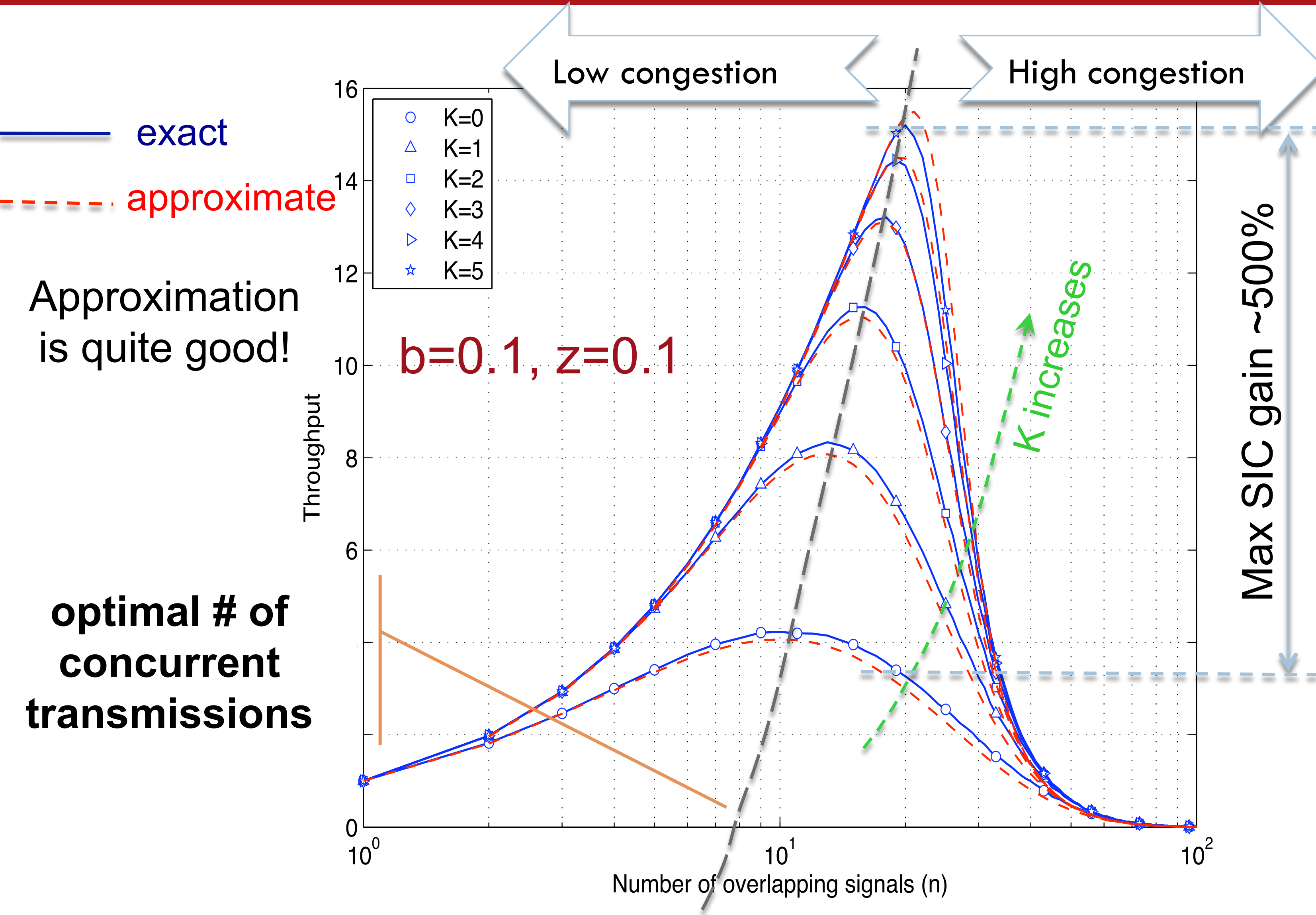
Throughput vs n



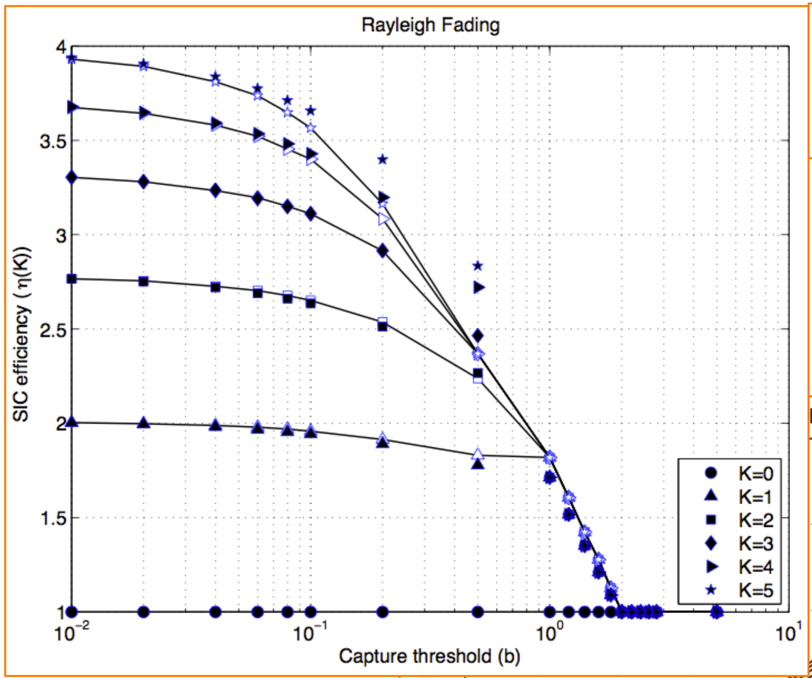
Approximation is quite good!

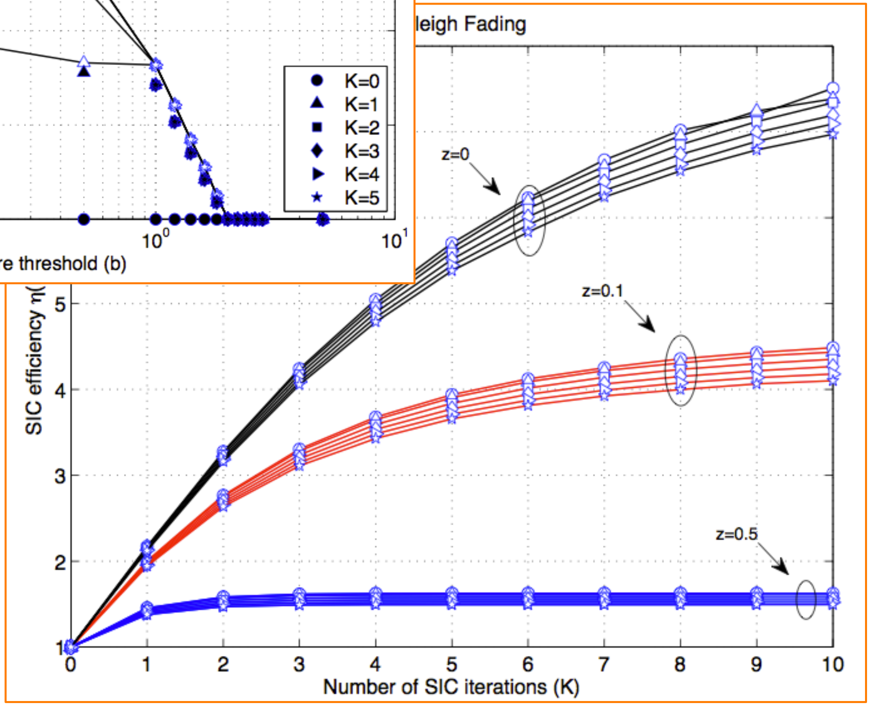
optimal # of concurrent transmissions

Max SIC gain analysis

- SIC is more effective with small b
- The less residual interference, the larger the SIC gain
- For K>1/z, SIC gain is negligible
  - Empirical conjecture

$$\eta(K) = \frac{\max_n\{S_n^{(s)}(K)\}}{\max_n\{S_n^{(s)}(0)\}}$$





An example of application to network planning

- Goal: dimensioning an MPR access point
- Given parameters:
  - Users' spatial distribution: Poisson process with density δ
- Performance metric: average throughput $S_D(K)=E[S_n(K)]$
- Knobs
  - Cell radius: *D*
  - Capture threshold: *b*
  - MPR capability: *R*
  - SIC capability: *K*
  - Power control capabilities
    - NoPC: No power control → Path Loss propagation model (PL)
    - SPC: Slow power control → Rayleigh Fading (RF)
    - FPC: Fast power control → LogNormal (shadowing) fading (LN)

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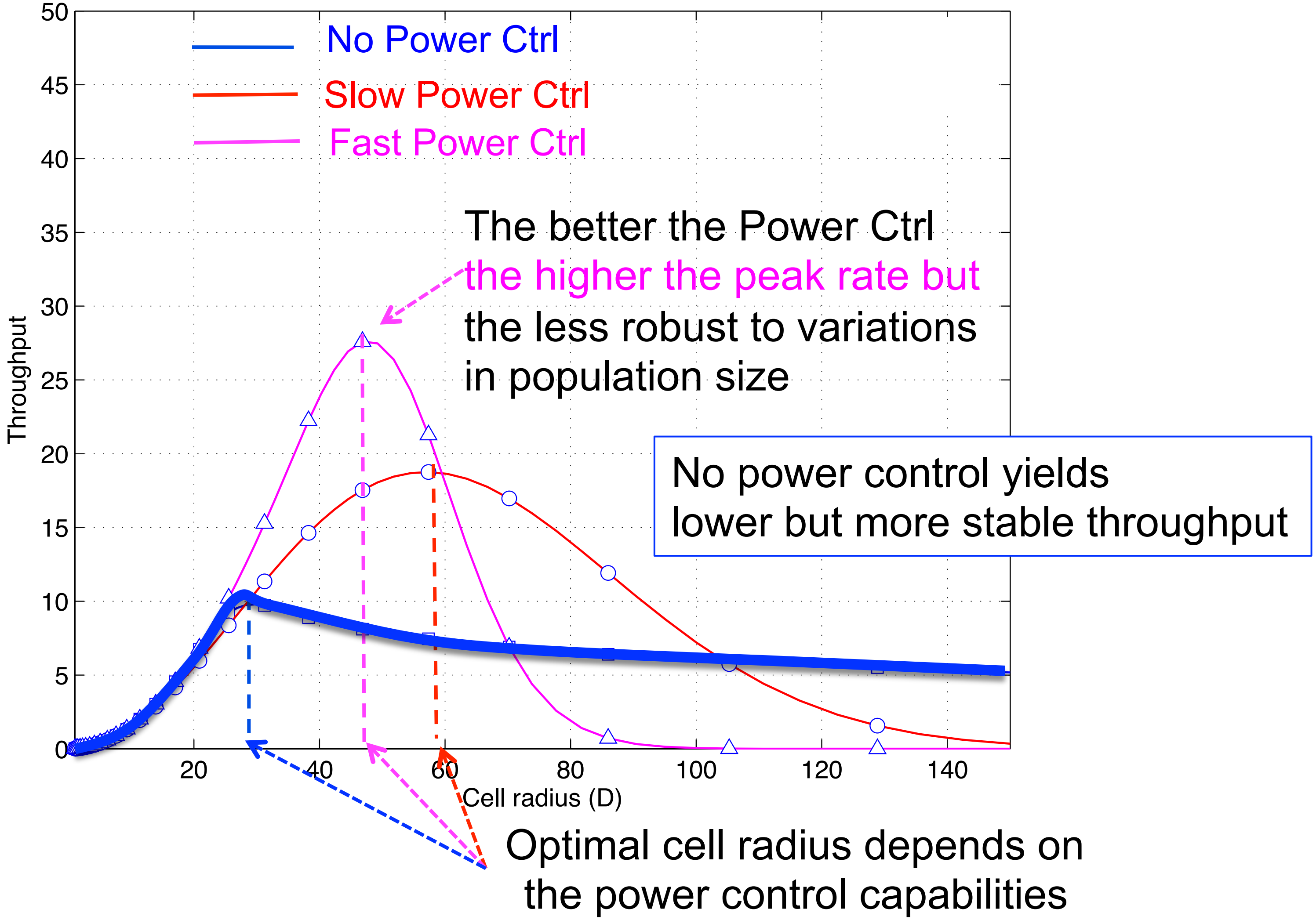
1 st step: determine throughput when varying cell radius with infinite MPR and no SIC



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2nd step: determine the number of MPR cycles

- Focusing on the No Power Control case we set the cell radius to D=50m
- Using our equations we find the minimum MPR capability R_m of the receiver beyond which the performance gain becomes negligible
  - we can set $R_m = \arg\min_R \{S_n(R)/S_n(\infty) \geq 1 - \rho\}$ where ρ is the maximum acceptable performance loss
  - In our example, R_m=15 yields less than 10% of throughput loss

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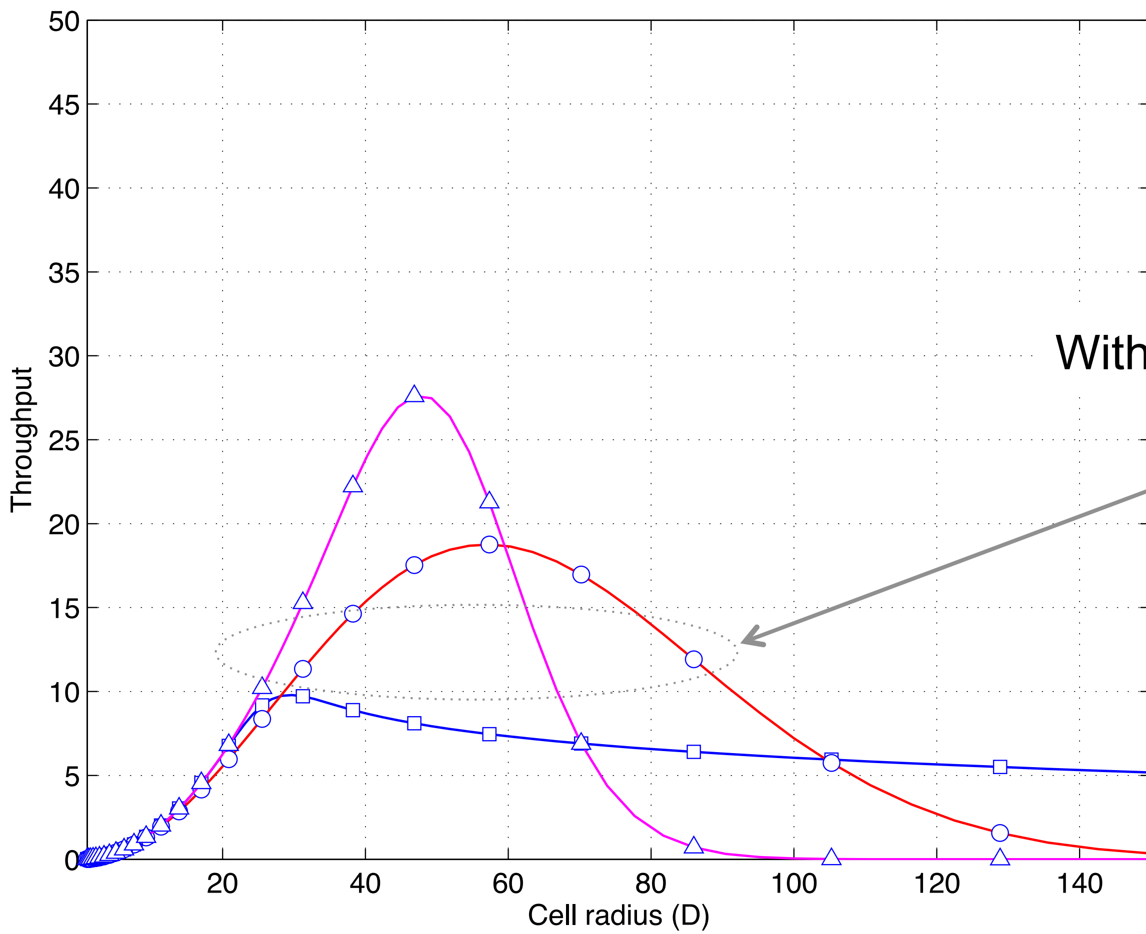
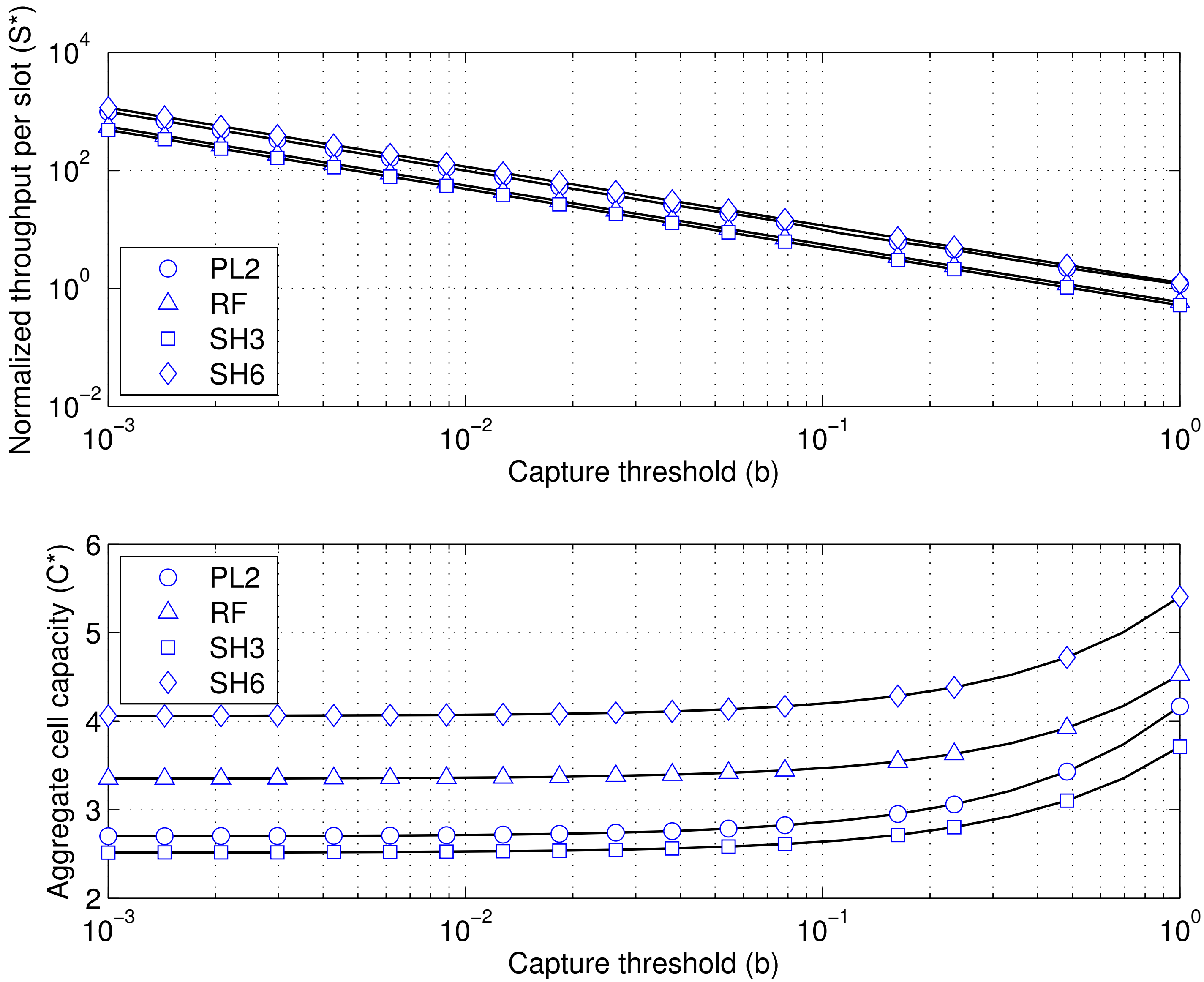
3rd step: introduce SIC



With just 1 SIC cycle

No SIC

Asymptotic performance



Zanella et al. "M2M massive wireless access: challenges, research issues, and ways forward" – Globecom 2013

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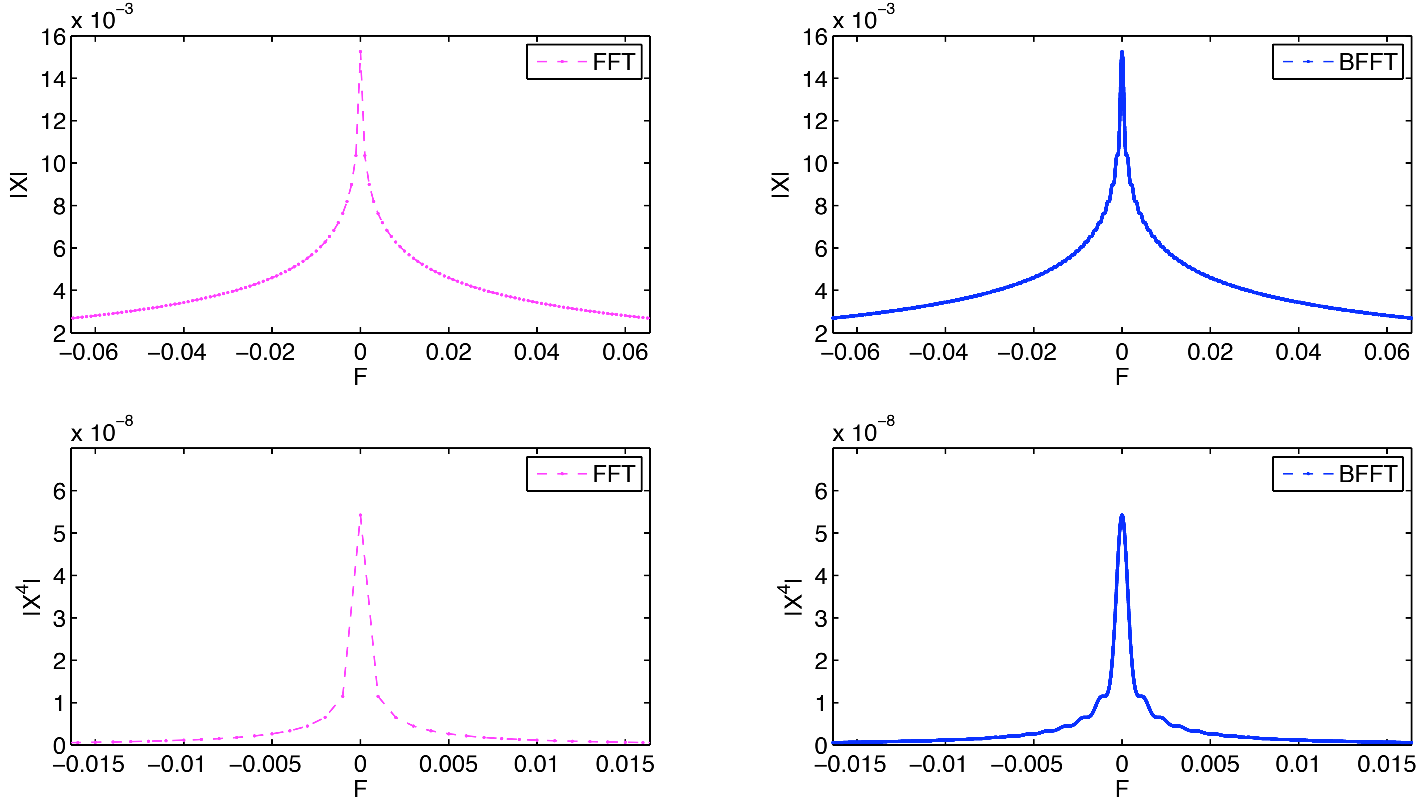
- Zanella et al. "M2M massive wireless access: challenges, research issues, and ways forward" – Globecom 2013

Spare slides

Break!!!! We all need it!

Bluestein FFT algorithm



- FFT samples are equally spaced over the entire signal bandwidth
- When raising the FTs to a power >1 most of such samples reduce to zero!
- Bluestein's FFT algorithm (BFFT) ``squeezes'' the samples into a fraction of the original bandwidth, so that samples are still significant after power raising

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Rayleigh fading

- Exponential distribution of the received power P_i

$$f_P(x) = \exp(-x)1(x); \quad F_P(x) = \left[1-\exp(-x)\right]1(x);$$

- Fourier Transform of the auxiliary rv $\alpha(u,v)$

$$\Psi_{\alpha(u,v)}(\xi) = \frac{e^{-u(i2\pi\xi+1)} - e^{-v(i2\pi\xi+1)}}{(1+i2\pi\xi)\left(e^{-u} - e^{-v}\right)}$$

- Mean value of $\alpha(u,v)$

$$m_{\alpha(u,v)} = \frac{(u+1)e^{-u} - (v+1)e^{-v}}{e^{-u} - e^{-v}}$$

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Appendix: asymptotic throughput

$$\mathcal{T}^\star(n) \simeq \frac{n}{\Lambda}.$$

$$\begin{aligned}\frac{n}{\Lambda} &\simeq \mathrm{E}\left[y_{w_n^\star,n}\right] + \sum_{s=0}^{\infty} \frac{n-s}{\Lambda} p_{w_n^\star,n}(s) \\ &\simeq \mathrm{E}\left[y_{w_n^\star,n}\right] + \frac{n}{\Lambda} - \frac{\mathrm{E}\left[S\right]}{\Lambda},\end{aligned}$$

$$\boxed{\Lambda \simeq \frac{\mathrm{E}\left[S\right]}{\mathrm{E}\left[y_{w_n^\star,n}\right]}.}$$

$$\Lambda \simeq \frac{w_n^\star n q_n^\star (1-q_n^\star)^{n-1}}{\beta_p + w_n^\star[\beta_c + (1-q_n^\star)^n(\beta-\beta_c) + n q_n^\star(1-q_n^\star)^{n-1}(1-\beta_c)]},$$

Appendix: asymptotic throughput

$$\mu_n = n q_n^\star \,, \qquad \mu_\infty = \lim_{n\to\infty} \mu_n \,.$$

$$\Lambda = \frac{\mu_\infty e^{-\mu_\infty}}{b_p + \beta_c + e^{-\mu_\infty}(\beta - \beta_c) + \mu_\infty e^{-\mu_\infty}(1 - \beta_c)}$$

Taking the derivative wrt mu_infty $\mu_\infty = 1 + \frac{\beta - \beta_c}{b_p + \beta_c} \exp(-\mu_\infty) \,,$

$$\boxed{\Lambda = \frac{e^{-\mu_\infty}}{b_p + \beta_c + e^{-\mu_\infty}(1 - \beta_c)} \,,}$$

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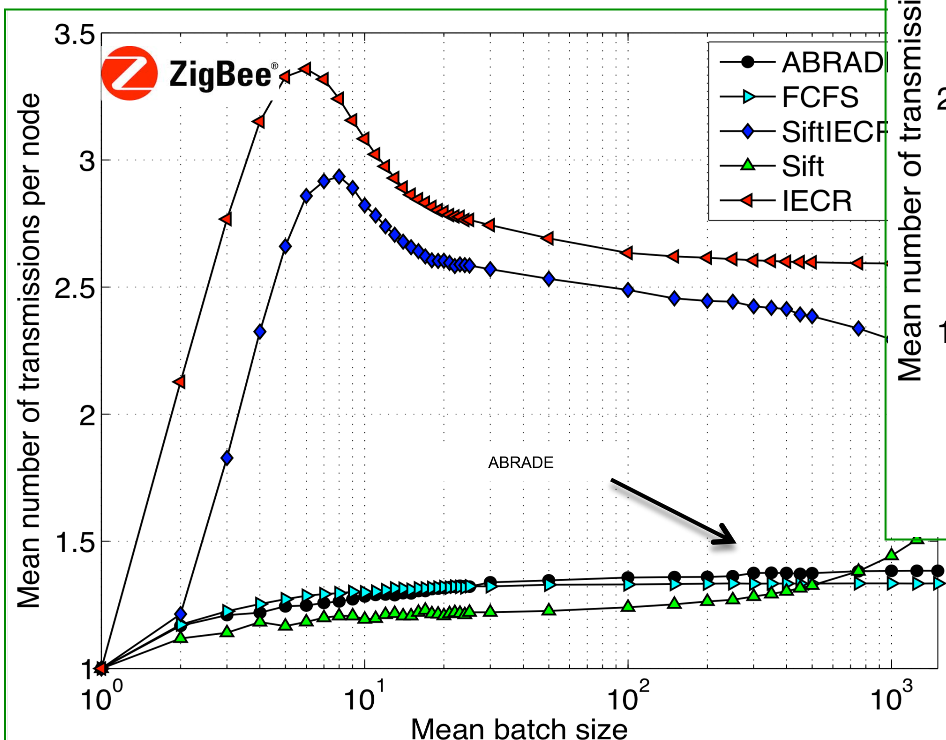
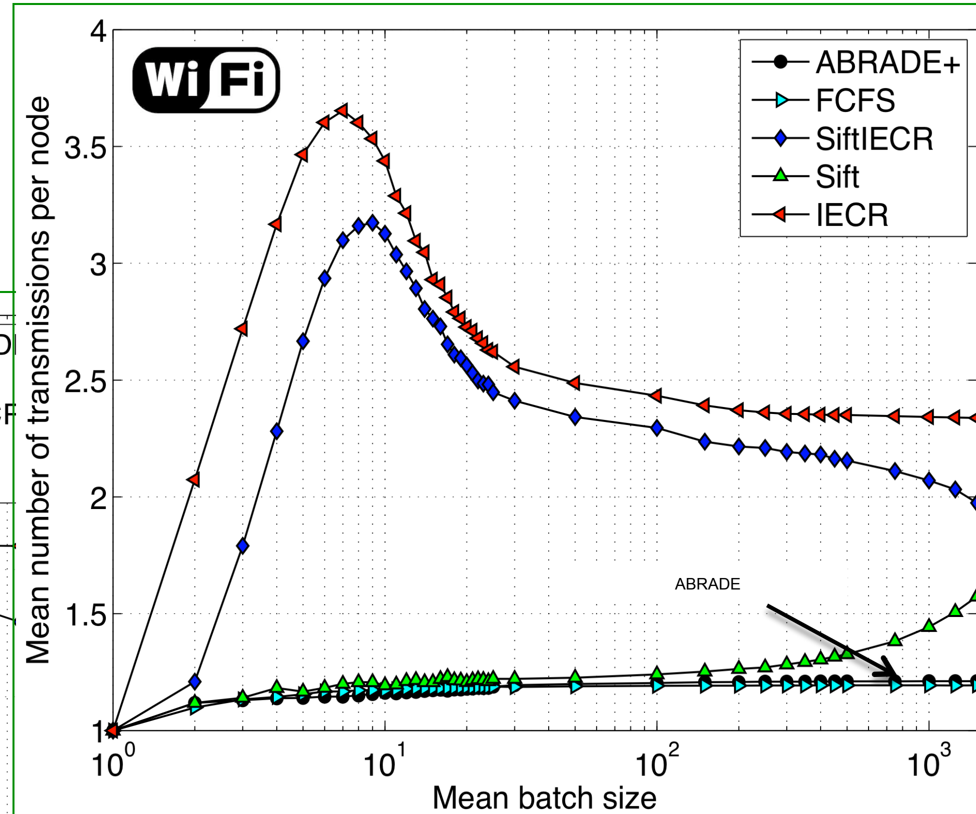
1. Poisson: Energy efficiency

- Mean number of tx per slot (proportional to energy consumption) comparable to the best performing algorithms





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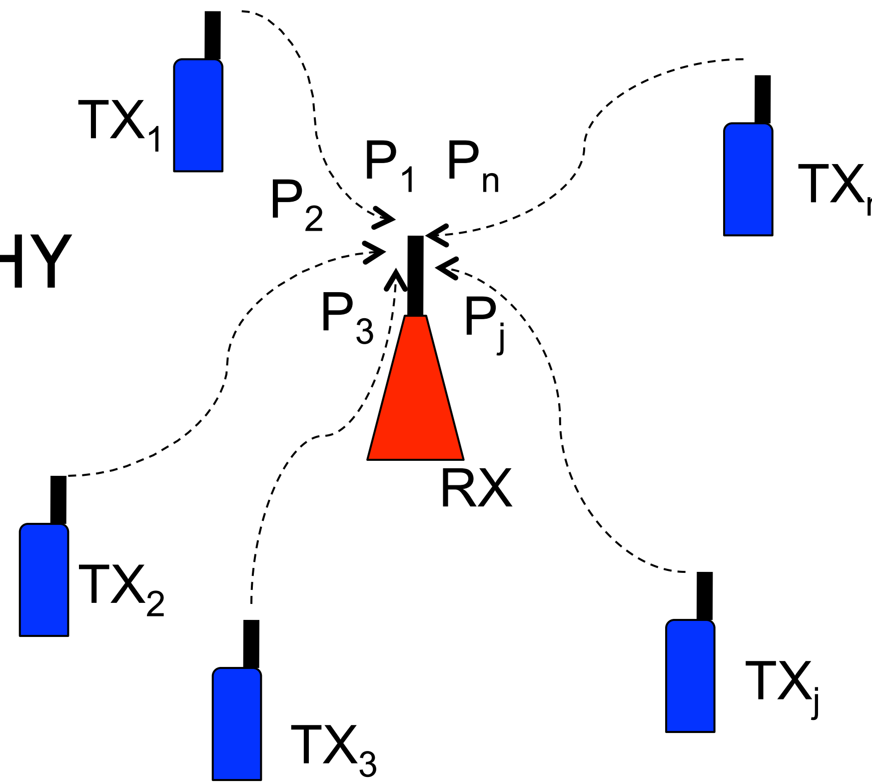
massive asynchronous access

- approach
  - move complexity to BS
  - use advanced MAC/PHY
    - MPR: multi packet reception
    - SIC: successive interference cancellation



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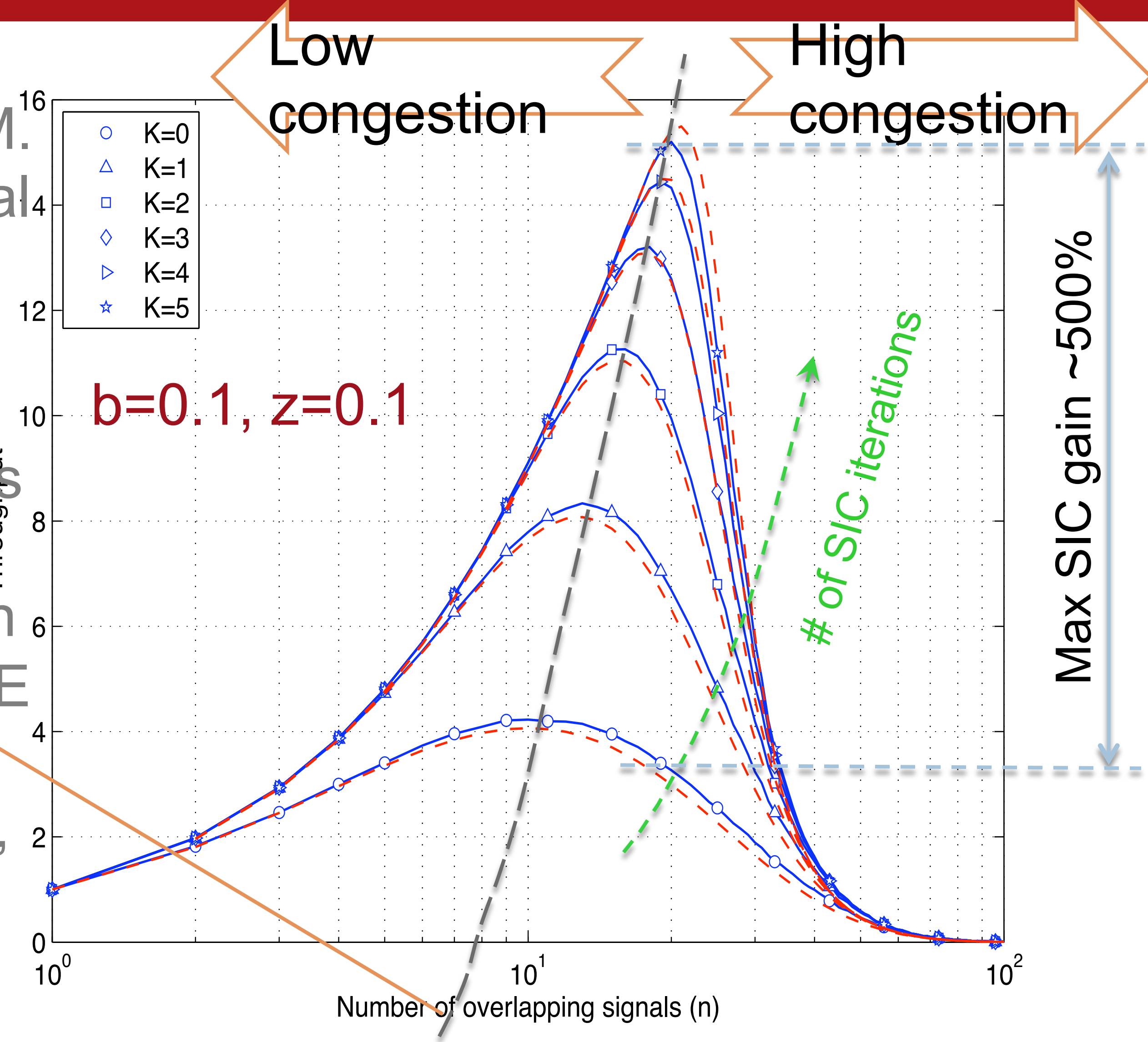
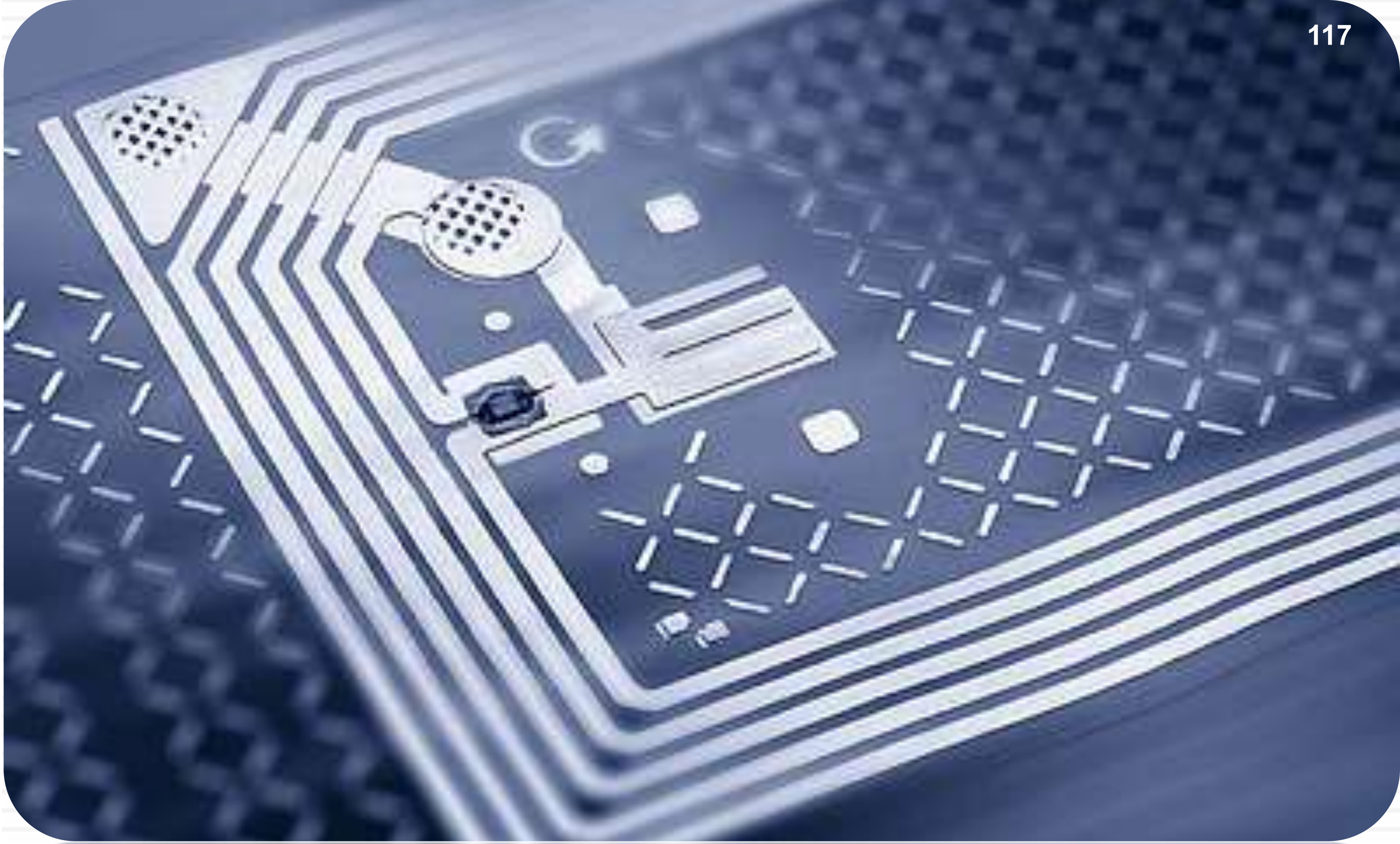
SIC+MPR throughput

A. Zanella, and M. Zorzi, "Theoretical Analysis of the Capture Probability in Wireless Systems with Multiple Packet Reception Capabilities" IEEE Transactions on Communications, 2012

optimal # of concurrent transmissions





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What is RFID

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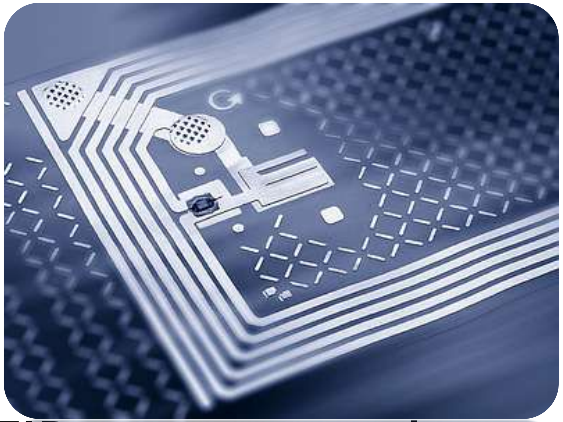
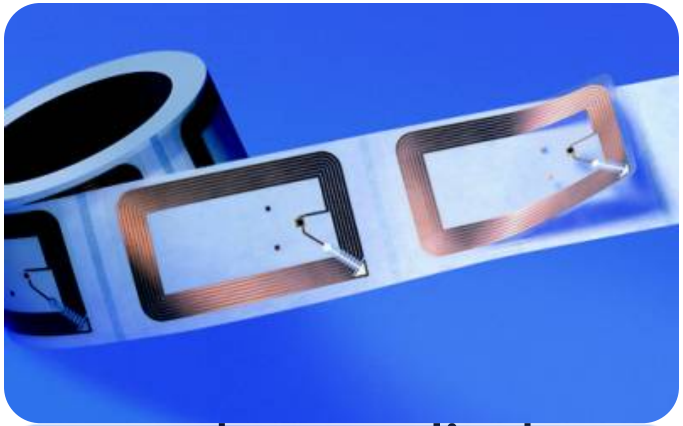
What is RFID

- RFID = Radio Frequency Identification





- An RFID tag is an object that can be applied to or incorporated into a product, animal, or person for the purpose of identification using radiowaves
- Some tags can be read from several meters away and beyond the line of sight of the reader

Wikipedia definition of RFID

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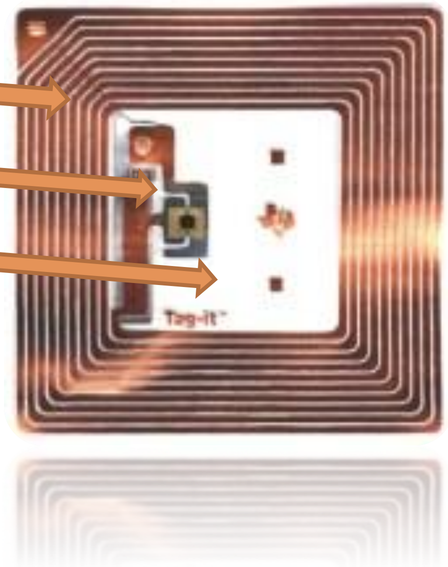
Components and types of RFID tag

- Antenna: for receiving and transmitting the signal
- Integrated Chip
- Plastic Inlay
- Maybe sensor, battery, external memory…



TYPES

- **Passive**: no battery, the electrical current induced in the antenna by the incoming radio frequency signal provides just enough power in the tag to power up and transmit a response
- **Active**: internal power source, which is used to power the integrated circuits and broadcast the signal to the reader
- **Semipassive**: similar to active tags in that they have their own power source, but the battery only powers the microchip and does not broadcast a signal.

From Wikipedia

125/134 kHz
13,56 MHz
868/915 MHz
>2,4 GHz

international standard for RFID: Epc Gen2 *Electronic Product Code Generation 2:*

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Communication in passive tags

	Checksum		EPC Code (or User ID Code)								Lock	PC
Byte	0	1	0	1	2	3	4	5	6	7	0	0
Bit	0-7	8-15	0-7	8-15	16-23	24-31	32-39	40-47	48-55	56-63	0-7	0-7

Class I Tag Memory Structure

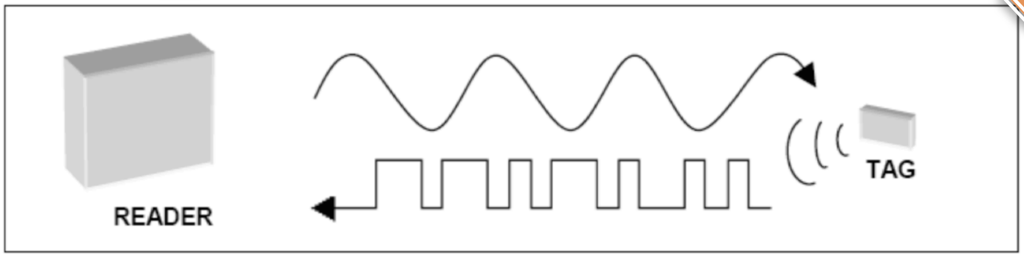
Image from Alien Guide

Reader transmits a wave signal

The tag's antenna gets the power

This power is sufficient to read the data saved in the chip

And transmit the answer to the reader



The reader transmits a continuous wave signal. The tag breaks up (modulates) that signal into patterns of ones and zeroes that convey its data to the reader.

Image from Alien Guide

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RFID vs BAR CODE

RFID

- Is possible to attach a tag on many surfaces
- No line-of-sight
- Many informations and/or applications
- Can be reprogrammed in the field to reflect current information
- Cheap: 0,20 $

BAR CODE

- Now everything has a bar code
- Requires line-of-sight
- Only ID information
- Data is fixed at the moment the label is printed
- Cost free

..but RFID are not only for identification scope..