Recent Advances in Communication Schemes for Massive Uncoordinated and Unsourced Multiple Access

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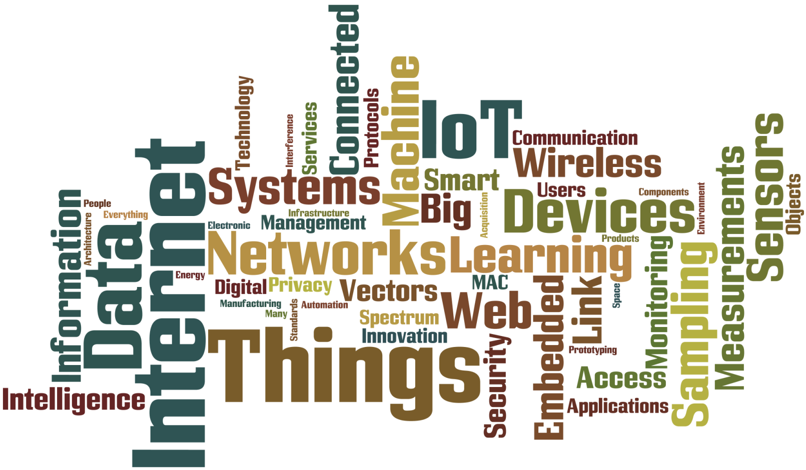
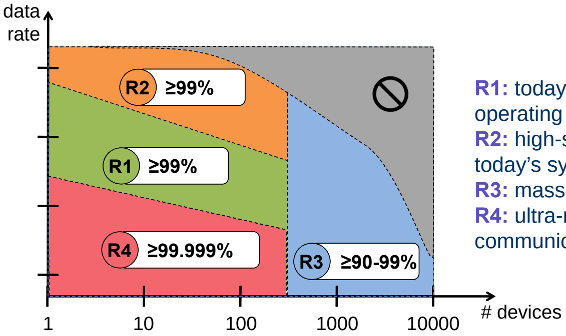
Internet of Things & Anticipated Device Growth



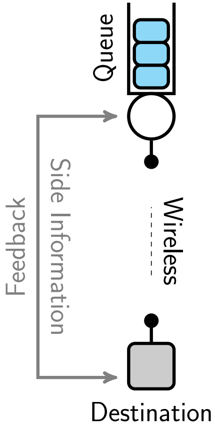
Motivation for Massive Multiple Access

- Current: A few devices with sustained connections
- 5G: Not just *4G but faster*; includes IoT and M2M communication
- Future: **Many uncoordinated** devices with **sporadic transmissions**



R1: today's systems operating region
R2: high-speed versions of today's systems
R3: massive access
R4: ultra-reliable communication

An Evolving Wireless Landscape



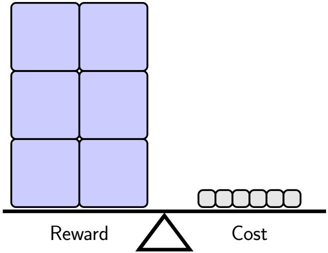
Conventional Systems

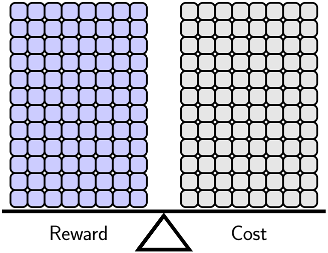
- Human operators, sustained connections
- Scheduling decisions based on channel quality & queue length
- Acquisition of side information amortized over long connections

Envisioned IoT Environments

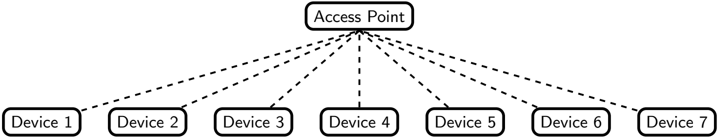
- Machine-to-machine communications
- Sporadic single transmissions from large number of devices
- Minute payloads

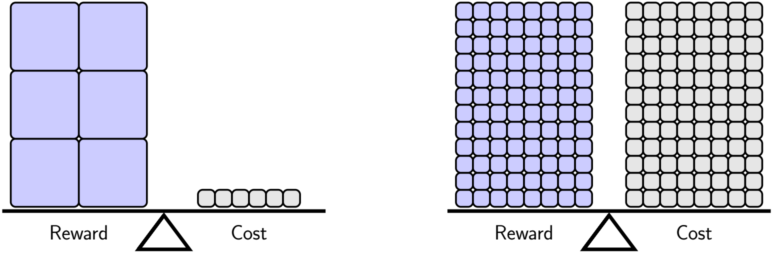
The Cost of Acquiring Side Information





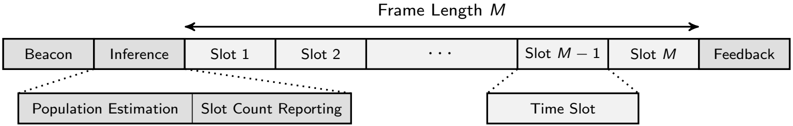
Uncoordinated Massive Multiple Access





Possible MAC Frame Structure

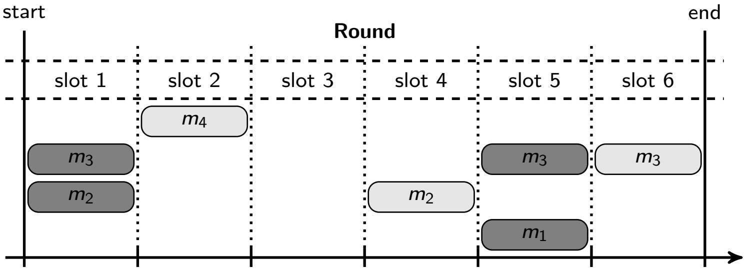
- K active devices out of Q devices
- Q is very large, and K is much less than Q



- Beacon is used to obtain coarse synchronization
- Each device transmits a signature sequence
- Access point estimates # of devices K
- Picks frame length M and inform devices

[1] X. Chen and D. Guo. "Many-access channels: The Gaussian case with random user activities." ISIT, 2014.

Random Access – Revisiting the Tradition

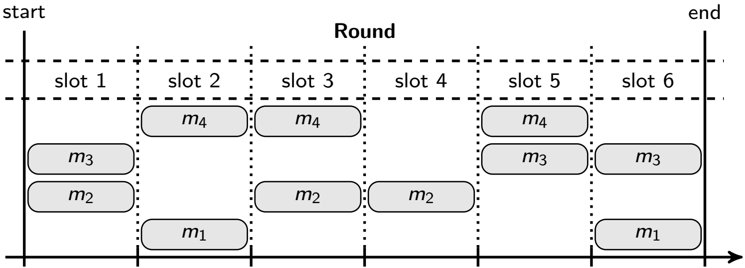


Slotted ALOHA

- K **uncoordinated** devices
- Time is **slotted**; transmissions occur within slots
- Collided packets are discarded
- Receiver provides **feedback** about collision events
- Back-off strategy determines performance, bounded by $1/e \approx 0.37$

[1] N. Abramson, "The ALOHA system: Another alternative for computer communications," in Proc. Computer Conference (1970).

Random Access with Twist



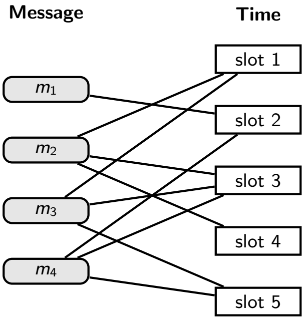
System Model

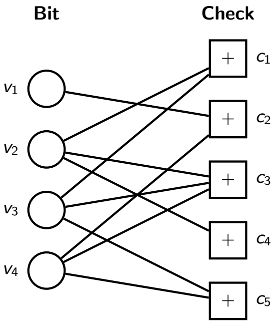
- K **uncoordinated** devices, each with 1 packet to send
- Time is **slotted**; transmissions occur within slots
- Receiver knows full schedule, collection of packets in every slot
- Successive interference cancellation

[1] E. Casini, R. De Gaudenzi, and O. Del Rio Herrero. "Contention resolution diversity slotted ALOHA (CRDSA): An enhanced random access scheme for satellite access packet networks." IEEE Trans. on Wireless Communications (2007).

Graphical Representation

- Tanner graph representation for transmission scheme
- Variable nodes $\leftrightarrow$ packets; Check nodes $\leftrightarrow$ received signals
- Message-passing decoder (SIC) – **peeling decoder** for erasure channel



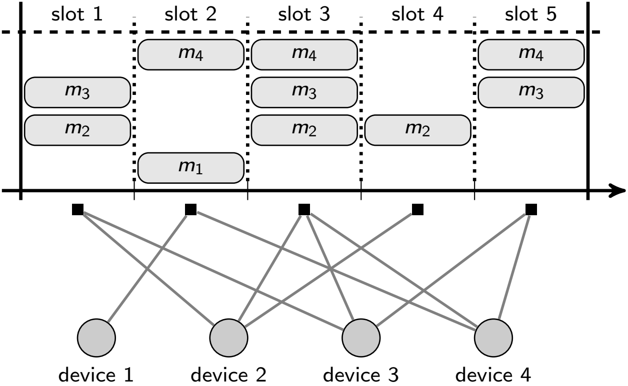


[1] G. Liva. "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA." IEEE Trans. on Communications (2011).

[2] E. Paolini, G. Liva, and M. Chiani. "Coded slotted ALOHA: A graph-based method for uncoordinated multiple access." IEEE Trans. on Information Theory (2015).

Decoder – Peeling Algorithm

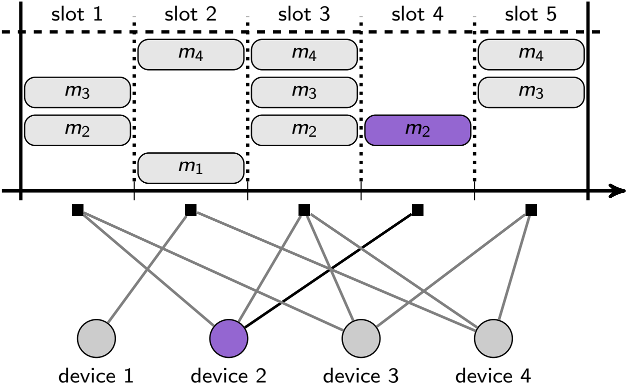
Joint decoding via successive interference cancellation



Instance of Random Access

Decoder – Peeling Algorithm

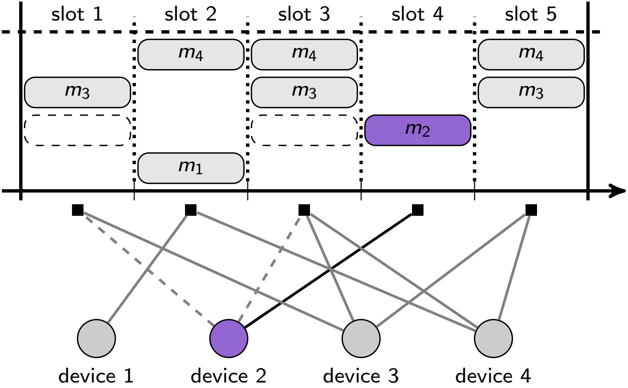
Joint decoding via successive interference cancellation



Step 1

Decoder – Peeling Algorithm

Joint decoding via successive interference cancellation



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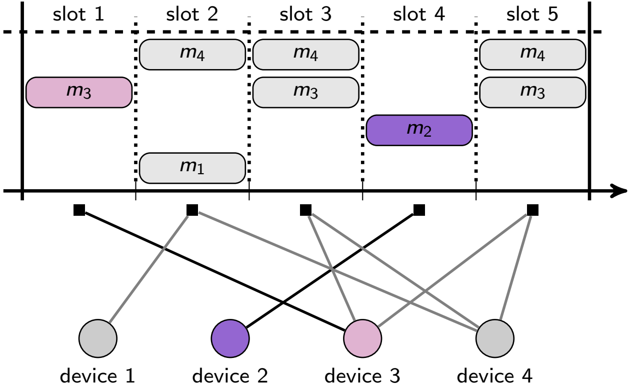
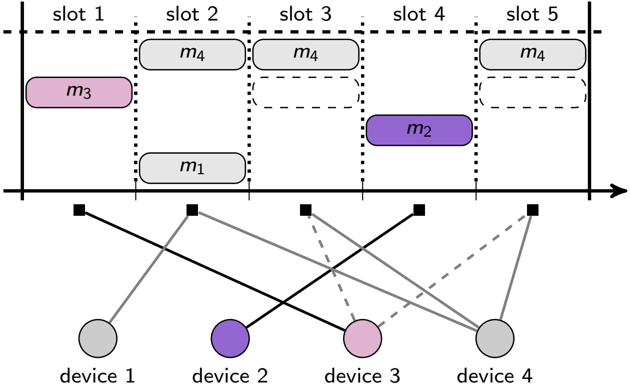


Step 2

Decoder – Peeling Algorithm

Joint decoding via successive interference cancellation



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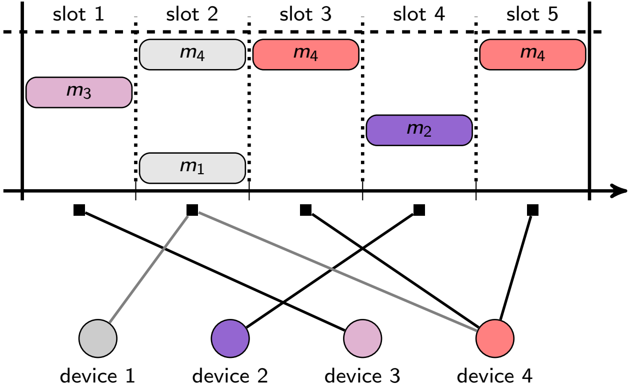
Decoder – Peeling Algorithm

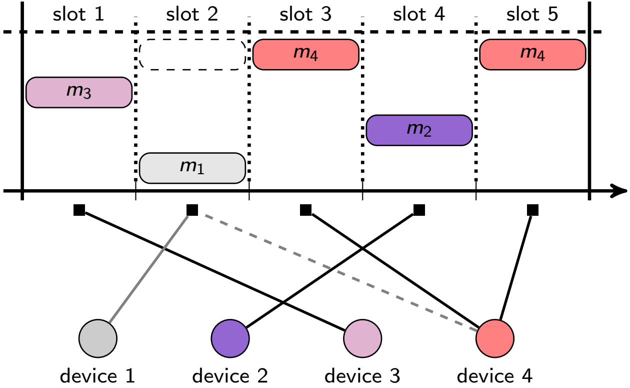
Joint decoding via successive interference cancellation



Step 3

Decoder – Peeling Algorithm

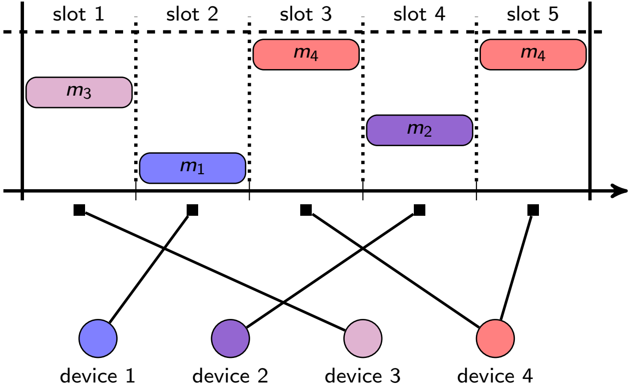
Joint decoding via successive interference cancellation



Step 3

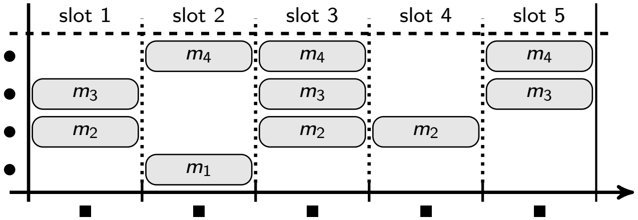
Decoder – Peeling Algorithm

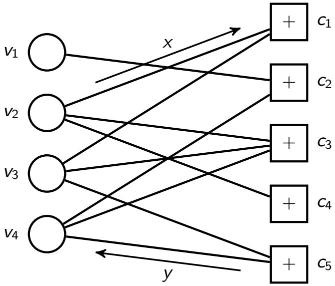
Joint decoding via successive interference cancellation

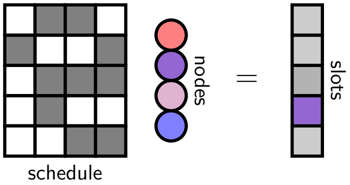


Step 4

Representations: Schedule, Tanner Graph, Compressed

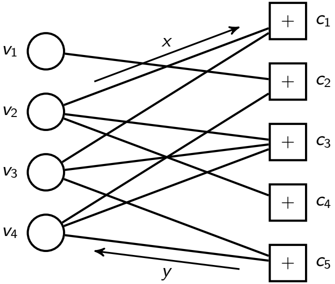


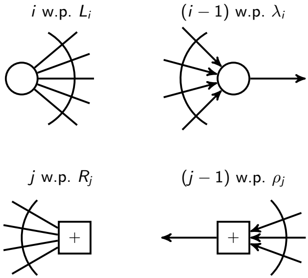




Graphical Methods: Tools from Iterative Decoding

- $L(z) = \sum_i L_i z^i$ variable dist. from node
- $\lambda(z) = \sum_i \lambda_i x^{i-1} = L'(z)/L'(1)$ variable dist. from edge
- $R(z) = \sum_j R_j z^i$ check dist. from node
- $\rho(z) = \sum_j \rho_j x^{j-1} = R'(z)/R'(1)$ check dist. from edge





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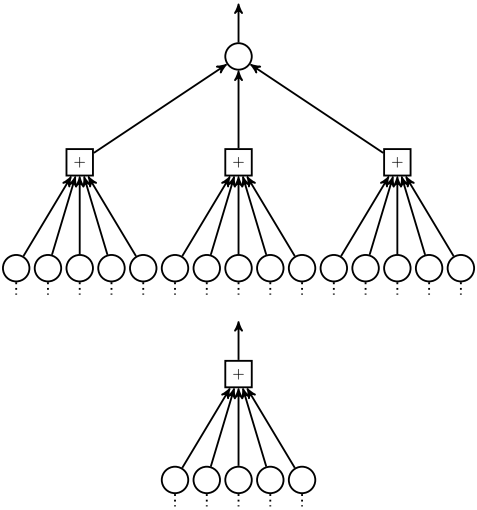
[1] V. Zyablov, and M. Pinsker. "Decoding complexity of low-density codes for transmission in a channel with erasures." Problemy Peredachi Informatsii (1974).

Computation Tree and Message Passing



Standard Tricks

- Unravel bipartite graph into computation graph
- For large systems, graph is locally tree-like
- Focus on outgoing messages
- Analyze over random code ensemble

[1] M. Luby, M. Mitzenmacher, A. Shokrollahi, and D. Spielman. "Efficient erasure correcting codes." IEEE Trans. on Information Theory (2001).

Graphical Methods: Tools from Iterative Decoding

- x: Prob. outgoing message from variable node erased
- y: Prob. outgoing message from check node erased

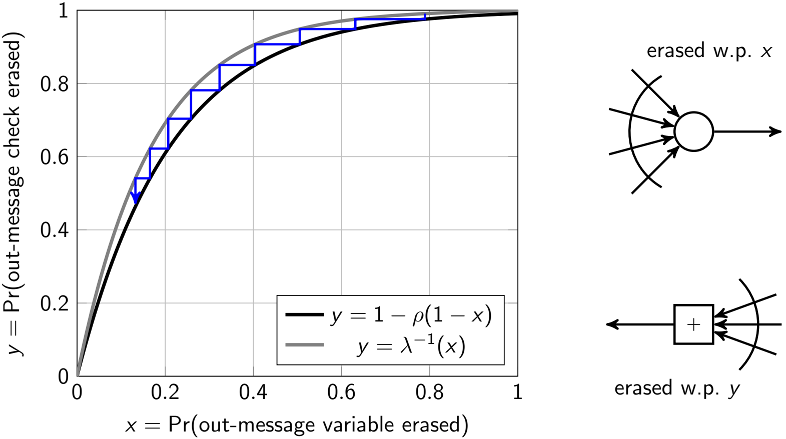
- Outgoing variable message is erased when all incoming check messages are erased

$$x = \mathrm{E}\left[y^{i-1}\right] = \lambda(y)$$

- Outgoing check message is erased when one incoming variable message is erased

$$y = \mathrm{E}\left[1-(1-x)^{j-1}\right] = 1-\rho(1-x)$$

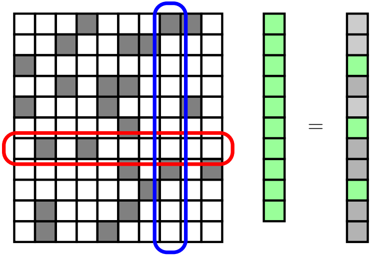
Extrinsic Information Transfer (EXIT) Chart



Step-by-Step Progression

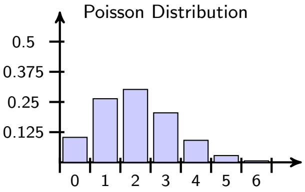
$$y = 1 - \rho(1 - x) \qquad\qquad x = \lambda(y) \quad \text{(flipped)}$$

Example – Traditional Fountain Codes

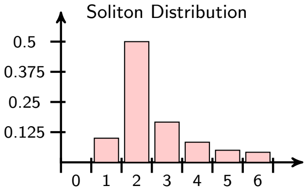


- Select # of bit nodes
- Pick bits uniformly
- Columns not selected independently
- Cannot be employed in massive uncoordinated multiple access

Variable Node Degree Distribution $L(\cdot)$

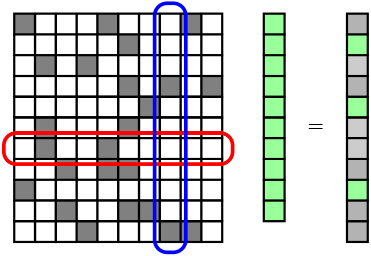


Check Node Degree Distribution $R(\cdot)$



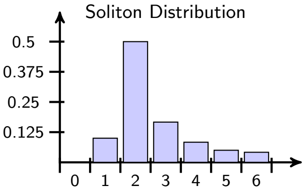
[1] K. Narayanan and H. Pfister. "Iterative collision resolution for slotted ALOHA: An optimal uncoordinated transmission policy." ISTC, 2012.

Example – Transpose of LT Codes

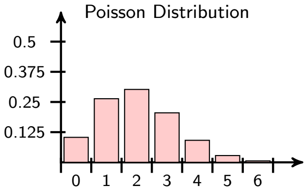


- Devices pick # of transmissions
- Selects slots uniformly
- Columns are independently
- Admissible massive uncoordinated multiple access

Variable Node Degree Distribution $L(\cdot)$



Check Node Degree Distribution $R(\cdot)$



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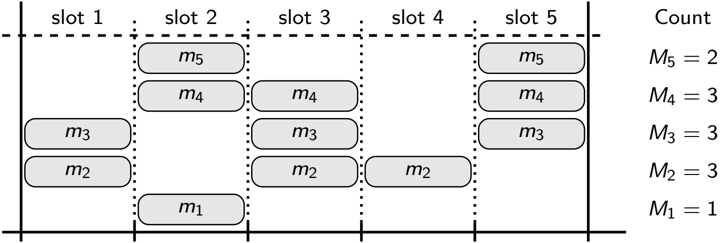
Optimal Scheme when Number of Devices Known



- Every device picks random slot count according to Soliton

$$p_{\mathrm{sol}(t)}(m) = \begin{cases} 1/t & m = 1 \\ 1/((m-1)m) & m = 2, \ldots t \end{cases}$$

- Given count, select m slots uniformly at random
- Induce Soliton on left and Poisson on right of Tanner graph
- Asymptotically **optimal** when number of devices is known

Proof Sketch – Access with Dual Fountain Codes

LT Codes

- Degree distributions

$$L(\cdot) \text{ Poisson dist}$$
$$R(\cdot) \text{ Soliton dist}$$

- Fountain codes optimal (asymptotically)

$$\lambda(z) = e^{-r_{\mathrm{avg}}(1-z)}$$
$$\rho(z) = -\ln(1-z)$$

- Density evolution

$$y = 1 - \rho(1-x)$$
$$x = \lambda(y)$$

Uncoordinated MAC

- Degree distributions

$$\tilde{L}(\cdot) = R(\cdot) \text{ Soliton dist}$$
$$\tilde{R}(\cdot) = L(\cdot) \text{ Poisson dist}$$

- Density evolution

$$y = 1 - e^{-r_{\mathrm{avg}} x}$$
$$x = -\ln(1-y)$$

- Recursions

$$\begin{aligned} y_{t+1} &= 1 - e^{r_{\mathrm{avg}} \ln(1-y)} \\ &= 1 - (1-y)^{r_{\mathrm{avg}}} \end{aligned}$$

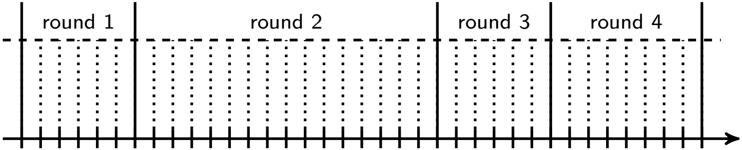
Throughput $\rightarrow 1$ when K known

Revised System Assumptions

- Devices operate with **no side information**, K unknown
- Access point broadcasts start/end of every round
- Joint decoding via successive interference cancellation: **peeling** algorithm

Other Considerations

- **Slots per round** can differ based on number of devices
- Perhaps length of round can be determined dynamically?



Universality

- Previous frameworks require the number of users to be known
  - to determine the round duration
  - or to determine the slot access probability (Frameless ALOHA)

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- Joint Estimation and Contention-Resolution-STPP'13[1]
  - Joint estimation of number of users and resolution of user packets
  - Multiple rounds, estimate of number of users is improved each round
  - Dynamic round durations as a function of fraction of users resolved

[1] [STPP'13] Č. Stefanović, K. F. Trilingsgaard, N. K. Pratas, P. Popovski, "Joint Estimation and Contention-Resolution Protocol for Wireless Random Access", IEEE ICC 2013.

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Our framework is universal: Does not require number of users to be known or estimated

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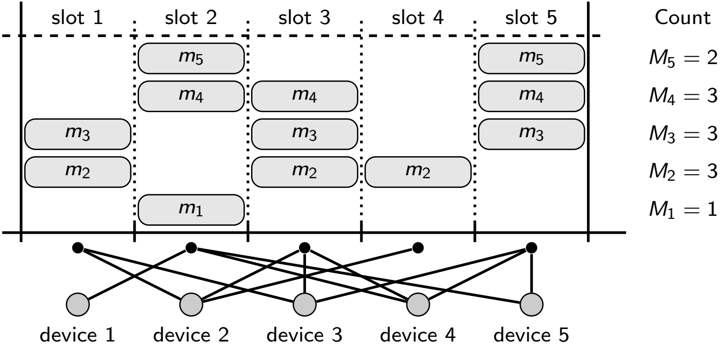
Soliton Distribution when Number of Devices Unknown



- When number of active devices is t, we want round to end after approximately t slots
- **First Guess:** When number of device is t, random slot count for each device at end time t should have Soliton distribution $p_{\mathrm{sol}(t)}(\cdot)$, independent of one another

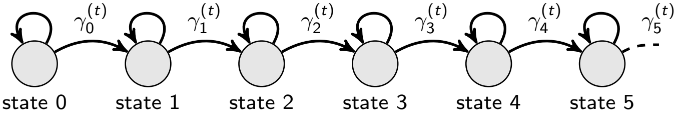
Challenge in Designing Universal Schemes

Challenge

- If device operates in isolation, it does not know total number of active devices nor slot count for current round
- Yet, packet count should have Soliton distribution $p_{\mathrm{sol}(s)}(\cdot)$ at end of round
- One way to fulfill requirement is for rolling message count to possess Soliton distribution $p_{\mathrm{sol}(s)}(\cdot)$ at every time s

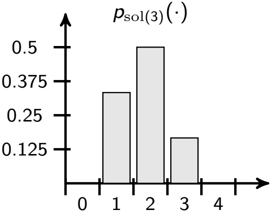
Can this be achieved?

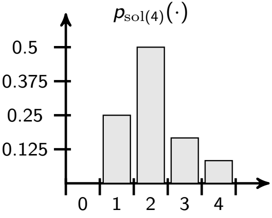
Potential Solution – Time-Varying Markov Chain



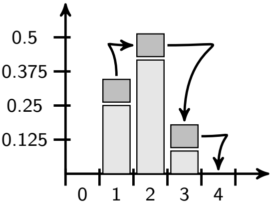
- Every device contains state machine initialized to 0 at onset of round
- Device transmits a copy of message whenever Markov chain jumps to right neighbor
- State denotes number of copies transmitted thus far
- Transition probabilities are time varying
- Progression of Markov chain independent from one device to another

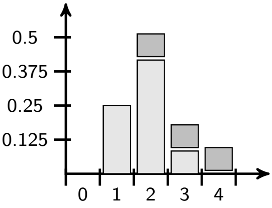
Computing Transition Probabilities



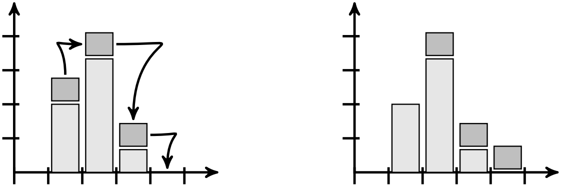


- Must find transition probabilities to shift from $p_{\mathrm{sol}(3)}(\cdot)$ to $p_{\mathrm{sol}(4)}(\cdot)$





Shifting from One Distribution to Another



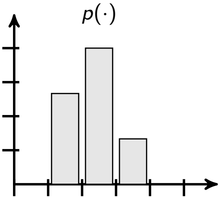
1. Condition 1: Need enough probability mass to push over to neighbor
2. Condition 2: Can't push probability mass past immediate neighbor
3. Conditions can be expressed mathematically in terms of first-order stochastic dominance

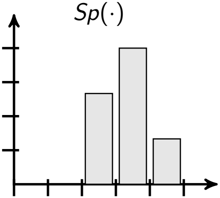
$$X \preceq Y \text{ whenever } \Pr(X > m) \leq \Pr(Y > m) \quad \forall m$$

or, equivalently, cumulative distribution function (CDF) of X dominates CDF of Y

Markov Chains and Distribution Shaping

- Let $p_0(\cdot), p_1(\cdot), p_2(\cdot), \ldots$ be a sequence of probability distributions
- Let S denote standard right shift operator acting on one-sided infinite sequences

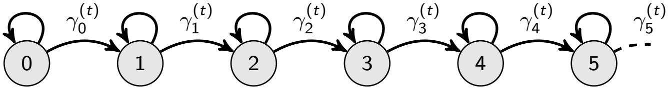




Theorem: Sequence of distributions can be achieved through monotone increasing Markov chain with self-transitions and transitions to nearest neighbors on the right iff

- $p_t \preceq p_{t+1}$ for every t – enough probability mass to push to right
- $p_{t+1} \preceq Sp_t$ for every t – cannot push mass past the neighbor

Applying Markov Shaping Strategy



- Suppose $p_0, p_1, \ldots$ is admissible sequence of distributions
- Let $\{X_t\}$ be first-order, time-inhomogeneous Markov chain
- Denote transition probabilities by

$$\Pr(X_{t+1} = m | X_t = m) = 1 - \gamma_m^{(t)}$$
$$\Pr(X_{t+1} = m+1 | X_t = m) = \gamma_m^{(t)}$$

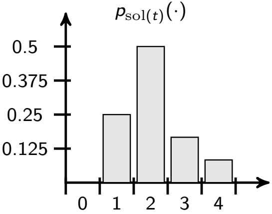
- Desired transition probabilities are

$$\gamma_m^{(t)} = \begin{cases} \frac{\sum_{\ell=0}^{m} p_t(\ell) - \sum_{\ell=0}^{m} p_{t+1}(\ell)}{p_t(m)} & p_t(m) > 0 \\ 0 & p_t(m) = 0 \end{cases}$$

Example: Soliton Distributions

Soliton Distribution

$$p_{\mathrm{sol}(t)}(m) = \begin{cases} \frac{1}{t} & m = 1 \\ \frac{1}{(m-1)m} & m = 2, \dots t \end{cases}$$



Checking Condition 1: $p_{\mathrm{sol}(t)} \preceq p_{\mathrm{sol}(t+1)}$

- CDF comparison yields

$$\sum_{\ell=0}^{m} p_t(\ell) - \sum_{\ell=0}^{m} p_{t+1}(\ell) = \frac{1}{t} - \frac{1}{t+1} = \frac{1}{t(t+1)}$$

- Difference vanishes for $m \geq t+1$
- Hence $p_{\mathrm{sol}(t)} \preceq p_{\mathrm{sol}(t+1)}$

Example: Soliton Distributions

Checking Condition 2: $p_{\mathrm{sol}(t+1)} \preceq Sp_{\mathrm{sol}(t)}$

- For $m = 1$, we have

$$\sum_{\ell=0}^{m} p_{t+1}(\ell) - \sum_{\ell=0}^{m-1} p_t(\ell) = \frac{1}{t+1} \geq 0$$

- For $m = 2, \ldots, t$, we get

$$\sum_{\ell=0}^{m} p_{t+1}(\ell) - \sum_{\ell=0}^{m-1} p_t(\ell) = \frac{1}{(m-1)m} - \frac{1}{t(t+1)} \geq 0$$

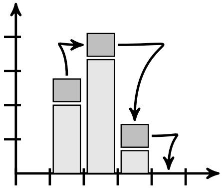
- Difference vanishes for $m \geq t+1$
- Hence $p_{\mathrm{sol}(t+1)} \preceq Sp_{\mathrm{sol}(t)}$

Example: Soliton Distributions

- Conditions 1 & 2 are **fulfilled**
- There exits **Markov chain** containing solely self-transitions and transitions to nearest neighbors on the right that possesses **Soliton distribution** at every time t

- Transition probabilities are

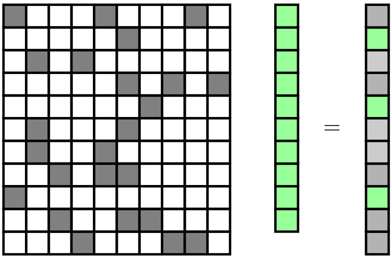
$$\gamma_m^{(t)} = \begin{cases} \frac{1}{t+1} & m = 1 \\ \frac{(m-1)m}{t(t+1)} & m = 2, \ldots, t \\ 0 & \text{otherwise} \end{cases}$$

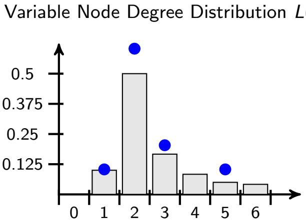


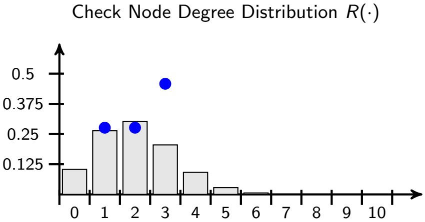
- Probability that device transmit during slot t is Wasserstein distance

Is this complete story?

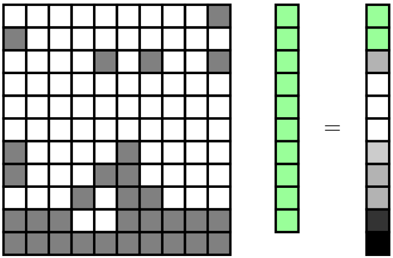
Realization of Standard Soliton Access Pattern (Goal)



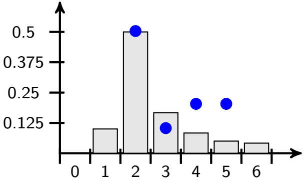




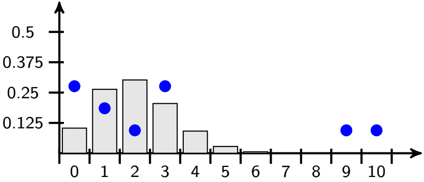
Realization of Markov Soliton Access Pattern (Outcome)



Variable Node Degree Distribution $L(\cdot)$



Check Node Degree Distribution $R(\cdot)$



Universal Framework with Markov Transmission Scheme

- Access point solely broadcast start/end of round
- Devices employ Markov chain to elect when to transmit
- Mathematical framework provide methodology to shape marginal distributions at every time step

Positive Aspects

- Design space is large in terms of distribution shaping
- Slot count can differ from number of active devices
- Stopping condition can include state of peeling decoder

Limitations

- Probability that device transmit packet is not uniform over time
- Tanner graph may be front-loaded
- Uniformly optimal universal scheme may not exist

Candidate Distributions Used in Numerical Results

Stateless Distributions

- Device use emission probabilities based on time elapsed

$$\gamma_m^{(t)} = \gamma^{(t)} = 1 - \exp\left(\frac{c \log(\epsilon)}{t}\right)$$

Skewed Distributions

- Skewed family favors nodes that have transmitted several packets

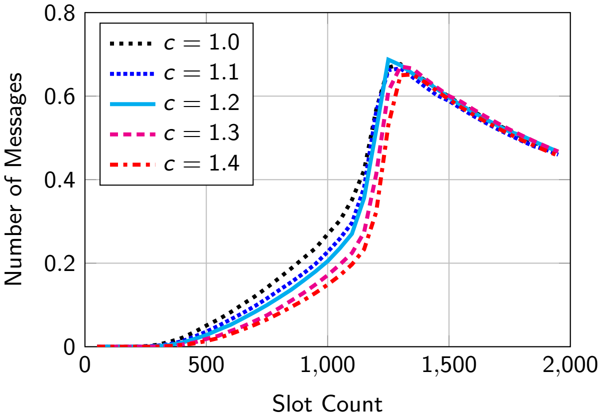
$$\gamma_m^{(t)} = \begin{cases} 0, & \sum_{i=0}^{m} p_t(i) < 1 - \overline{\gamma}^{(t)} \\ 1, & \sum_{i=m}^{t} p_t(i) \leq \overline{\gamma}^{(t)} \\ \frac{\overline{\gamma}^{(t)} - \sum_{i=m+1}^{t} p_t(i)}{p_t(m)} & \text{otherwise} \end{cases}$$

Skewed Distributions

In numerical results, we use mixture of these two families

Numerical Results – Parameterized Distribution

- Parameter 1: Number of time slots per round
- Parameter 2: Tuning factor to favor nodes that have already transmitted several copies of their messages
- **Performance Criterion:** average number of decoded packet per time slot (shown for 1250 devices)



Discussion – Universal Framework

- New framework for Universal Multiple Access
- Necessary and sufficient conditions for proposed approach
- Large design space need to be explored
- Efficiency shown up to 69 percent
- Substantially exceeds performance of traditional ALOHA
- Performance and complexity need to be compared with case where number of devices is estimated at onset of every round

Unsourced MAC

Assumptions

- K active devices out of Q devices
- Q is very large, and K is much less than Q
- Every device transmits a message

Access point interested in messages, not in identity of sources

Entropy of Identities

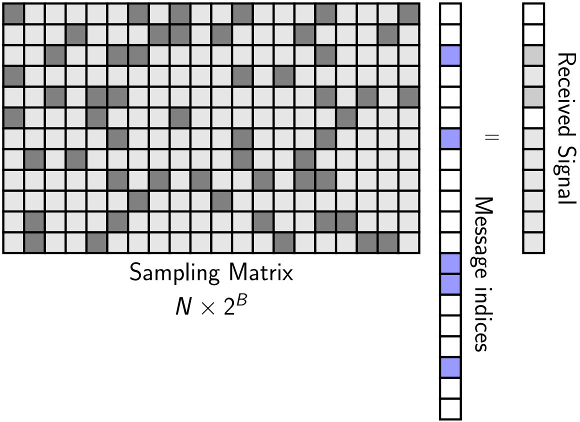
- Size of active subset is K
- Link identity of source to every message

$$\log_2 \frac{Q!}{(Q-K)!} = \mathcal{O}\left(K \log_2 Q\right)$$

- Explore alternate approches
- Performance bounds for Unsourced MAC with finite-length codes [1]

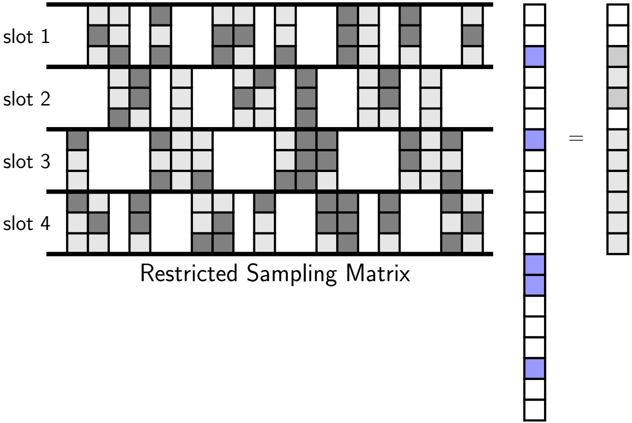
[1] Y. Polyanskiy. "A perspective on massive random access." ISIT, 2017.

Unsourced MAC – Compressive Sensing Viewpoint



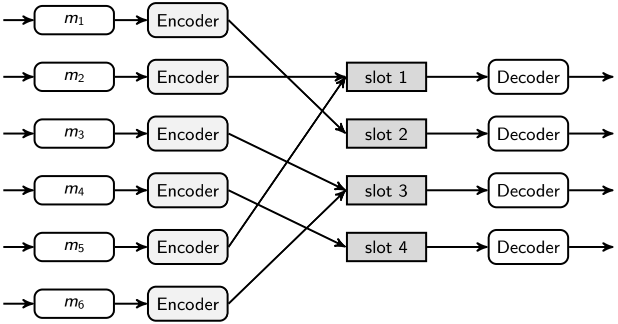
- $M = 2^B$ entries
- $K \approx 100$ active devices
- Non-negative coefficients
- $B \approx 100, N \approx 30,000$
- $\mathcal{O}(K \log M)$
- May be too large

Unsourced MAC – A Quest for Low Complexity



- Partition into V slot
- $\tilde{N} = N/V$ channel uses
- Aim is T-user adder channel
- Admits graphical representation

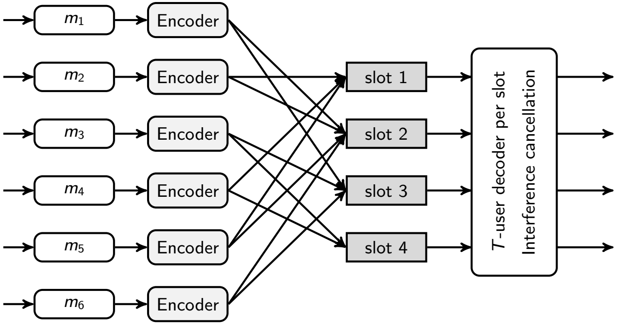
Unsourced MAC – Low Complexity State-of-the-Art



- Every active devices randomly select one sub-block
- Inner code designed to recover modulo-p sum of codewords
- Outer code is designed to decode multiple messages given the modulo-p sum of their codewords

[1] O. Ordentlich and Y. Polyanskiy. "Low Complexity Schemes for the Random Access Gaussian Channel." ISIT, 2017.

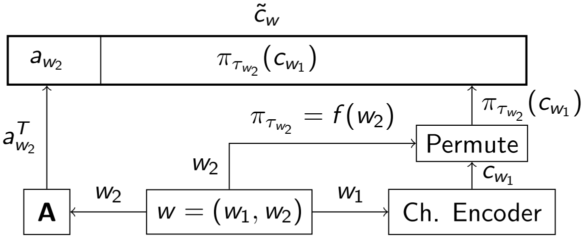
Unsourced MAC – Proposed Scheme



- Schedule selected based on **message**
- Devices can transmit in multiple sub-blocks
- Scheme facilitates successive interference cancelation

[1] A. Vem, K. Narayanan, J. Cheng, J.-F. Chamberland

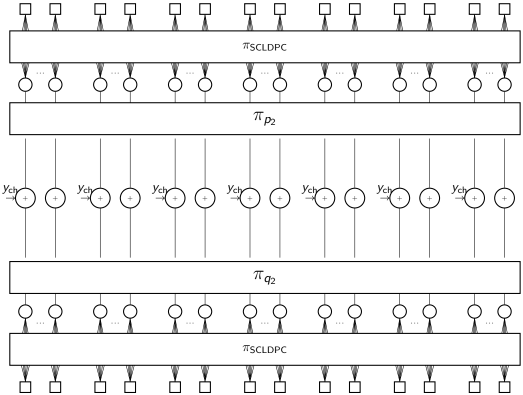
What Really Happens within Slot?



- Message is partitioned into two parts $w = (w_1, w_2)$
- Every device uses identical codebook built from LDPC-type codes tailored to T-user real-adder channel
- w_2 dictate permutation on encoder and recovered through CS
- Non-negative ℓ_1-regularized LASSO
- Spatially-coupled low-density parity check code is employed

[1] A. Vem, K. Narayanan, J. Cheng, J.-F. Chamberland

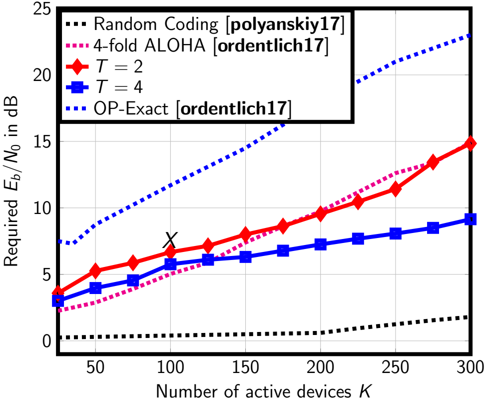
What Really Happens within Slot?



- Run joint belief propagation (BP) decoder

[1] A. Vem, K. Narayanan, J. Cheng, J.-F. Chamberland

Side by Side



- Minimum E_b/N_0 required as function of # of devices
- For $T = 2, 4$ and 4-fold ALOHA, prob. of decoding every slot ≥ 0.99
- Prob. recovered messages ≥ 0.96 given T-user decoding successful

[1]A. Vem, K. Narayanan, J. Cheng, J.-F. Chamberland

Discussion – Unsourced Multiple Access

- New framework for Unsourced Multiple Access
- Leverages power and lessons from graphical model
- Proposed scheme outperforms state-of-the-art
  - Takes advantage of successive interference cancellation
  - Relax requirement for keeping maximum devices per slot below T
  - Takes advantage of T-user real-adder channel via BP
- Complexity needs to be tracked better
- Design of sampling matrix A can be optimized

Questions?

Thank You