Network-Coded Cooperation: A Mathematical Perspective

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Collaborators

Main collaborators at the Deutsche Telekom Chair of Communication Networks

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- M.Sc. Sreekrishna Pandi

Outline

Network Coding (NC)

Random Linear Network Coding (RLNC) in wireless networks

- Novel paradigm in communications
- Reduces the number of transmissions
- Enhances throughput
- Overhead: decoding complexity
- Numerous "flavors":
  - Full-vector
  - Systematic
  - PACE
  - Sparse

Full-vector RLNC

Packets in the generation

$$\mathbf{G} = [\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3, \mathbf{p}_4]$$

Matrix of coefficients

$$\mathbf{M}_{\mathsf{FV}} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & \cdots & 1 \\ 0 & 1 & 1 & 0 & 1 & \cdots & 0 \\ 1 & 0 & 1 & 0 & 1 & \cdots & 0 \\ 0 & 0 & 1 & 1 & 1 & \cdots & 1 \end{bmatrix}$$

Systematic RLNC

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Cooperative Mobile Clouds (CMCs)

Cooperation [1]

1. The state of having shared interests or efforts (as in social or business matters)
2. The work and activity of a number of persons who individually contribute toward the efficiency of the whole

Mobile Clouds (MCs)

Cooperative arrangement of dynamically connected nodes sharing resources opportunistically[2]

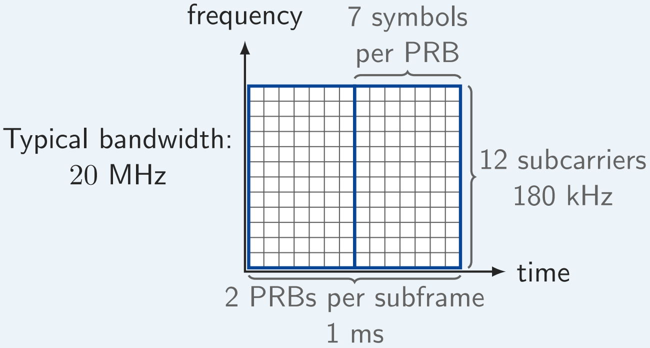
[1] Merriam Webster [Online]. Available: https://www.merriam-webster.com

[2] F. H.P. Fitzek and M. D. Katz (2014). *Mobile Clouds. Exploiting Distributed Resources in Wireless, Mobile and Social Networks*. United Kingdom: John Wiley and Sons, Ltd. ISBN: 978-0-470-97389-9.

Downlink data transmission in 4G LTE-A

Physical Downlink Shared Channel (PDSCH)[3]

Minimum unit for data transmission: physical resource block (PRB)



[3] 3GPP (2015). *Physical channels and modulation*. TS 36.211 V12.6.0.

Problem statement

LTE-A has no efficient mechanisms for massive content distribution[4]

Broadcast systems such as the eMBMS present several drawbacks

- Indoor coverage
- High energy consumption
- Low spectral efficiency

State of the art: One unicast session per user equipment (UE)

Existing cooperative systems implement unicast short-range links

Multicast in the short-range is much more efficient

[4] EBU (2014). *Delivery of Broadcast Content over LTE Networks.* Tech. rep.

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Solution: Network Coded Cooperation (NCC)

Combination of RLNC with CMCs

- Offload the LTE-A link
- Increase throughput
- Reduce energy consumption

But we need answers

- How to organize the UEs?
- How to transmit data?

Basic NCC protocol

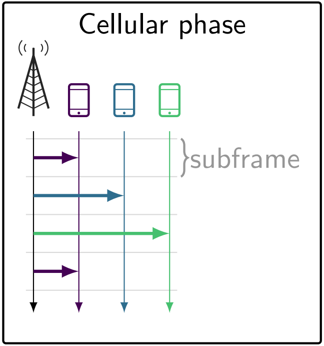
Cellular phase

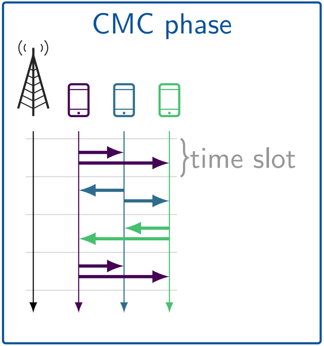
- eNB transmits g data packets in n time-multiplexed unicast sessions
- Data packets are distributed among the n UEs so they MUST cooperate

CMC phase

- UEs cooperate through multicast WiFi links.
- No ACKs are transmitted
- An RLNC scheme is implemented

Basic NCC protocol

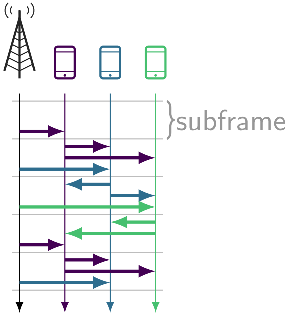




Protocol as in CCNC 2018 demo [5]

Scheduling

- Concurrent reception from LTE-A and WiFi links
- Improved throughput
- Practical in current smartphones?

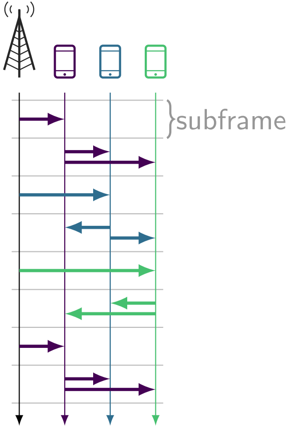


[5] S. Pandi, R. Torre, G. Nguyen, and F. H. P. Fitzek, "Massive Video Multicasting in Cellular Networks using Network Coded Cooperative Communication", demo presented at the IEEE CCNC/CES, 2018.

Protocol variant 1 (Pv1)

Scheduling

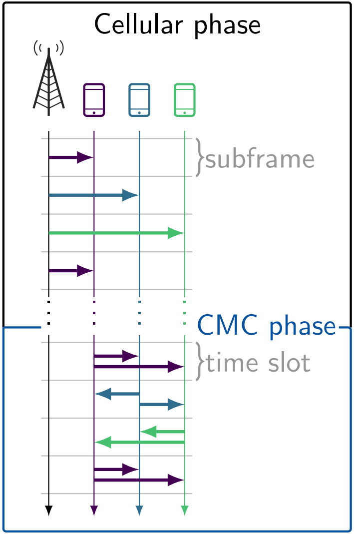
- Alternated LTE-A and WiFi transmissions
- Practical in current smartphones?
- Not flexible to different data rates
- Improved throughput?
- Improved packet latency?



Protocol variant 2 (Pv2)

Scheduling

- First LTE-A transmissions and then WiFi
- Practical in current smartphones
- Flexible to different data rates
- Improved throughput?
- Improved packet latency?



Mathematical tools

Probability and stochastic processes

- Random variables
- Probability mass function (pmf)
- Cumulative distribution function (CDF)
- Binomial distribution (binomial coefficient)

Markov chains

- Discrete-time
- Absorbing
- Transient analysis
- Phase-type distributions

Why discrete-time Markov chains (DTMCs)?

Reduced computational complexity

Those binomial coefficients are nasty, even Matlab® complains

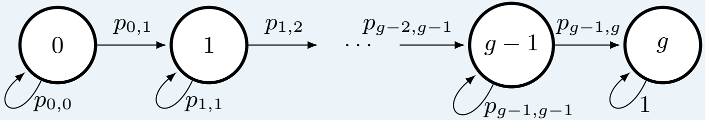
Example: negative binomial distribution

$$p_X(x) = \Pr[X = x] = \binom{n_t - 1}{n_s - 1} p_s^{n_s} (1 - p_s)^{n_t - n_s}$$

- $n_t \equiv$ number of trials
- $n_s \equiv$ number of successes
- $p_s \equiv$ probability of success

Example: DTMC for a negative binomial distribution

Graphical representation



We need

- $\boldsymbol{\alpha}^{(0)} = \left[\alpha_0^{(0)}, \alpha_1^{(0)}, \ldots, \alpha_{g-1}^{(0)}\right] \equiv$ vector of initial states
- $\mathbf{T} \equiv$ transition matrix
- $p_{a,b} \equiv$ transition probabilities
  - $p_{a,a+1} = p_s$
  - $p_{a,a} = 1 - p_s$

Example: DTMC for a negative binomial distribution

Transition matrix of size $g \times g$

$$\mathbf{T} = \begin{bmatrix} 1-p_s & p_s & 0 & \cdots & 0 \\ 0 & 1-p_s & p_s & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & p_s \\ 0 & 0 & 0 & \cdots & 1-p_s \end{bmatrix}$$

How to obtain the pmf

$$\boldsymbol{\alpha}^{(n_t)} = \boldsymbol{\alpha}^{(n_t-1)}\mathbf{T}$$

$$p_X(x) = \left[\boldsymbol{\alpha}^{(n_t)}, 1 - \sum_{n_s=0}^{g-1} \alpha_i^{(n_t)}\right]$$

Parameters

Parameter	Symbol
Generation size	g packets
Cloud size	n UEs
Field size	GF(q)
Time slots allocated for coded packet transmissions	s
Packet erasure rate (PER)	ϵ
Desired probability that the coding matrix of the n UEs is full rank (i.e., reliability)	τ

Notation

Notation	Definition
$N = \{i \in \mathbb{Z}_+ \mid i \leq n\}$	Set of UEs in the CMC
$N_i = \{j \mid j \in N \setminus i\}$	Set of neighbors of the ith UE
g_i packets	Packets transmitted from the eNB to the ith UE
t_i	Number of coded transmissions towards the ith UE
$X_{t_i}^{(i)}$	Rank of the coding matrix at the ith UE at time index t_i; domain: x
$Z_{t_i}^{(i,j)}$	Number of dofs missing at the coding matrices of both, the ith and jth UEs at time t_i; domain: z
$\mathbb{P}(t_i)$	Probability that the t_ith coded packet is innovative

Full-vector RLNC

Definition (Decoding probability under RLNC)

Let $\mathbf{C}$ be a coding matrix of size $r \times c$ s.t. $r \in \mathbb{Z}_{\geq 0}$, and $\{c \in \mathbb{Z}_{+} \mid c \leq g\}$, whose elements are selected uniformly at random from GF(q). The probability that matrix $\mathbf{C}$ is full-rank is given as

$$F_{\text{rlnc}}(r, c) = \begin{cases} 0 & \text{for } r < c, \\ \prod_{j=0}^{c-1} \left(1 - q^{j-r}\right) & \text{otherwise.} \end{cases} \tag{1}$$

Challenges: Protocol design

No ACKs are transmitted and generations are transmitted one after the other

- How many transmissions are needed to decode with a certain reliability?
- Which packets should the UEs recode?
- What is the best RLNC scheme for our protocol?
- Field size 2 or 2^8?
- How to organize the cellular and CMC phases?

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  Systematic over full-vector
- Field size 2 or 2^8?
  energy consumption: communication vs decoding
- How to organize the cellular and CMC phases?
  Protocol variant 2: packet latency vs flexibility

What is the best RLNC scheme for our protocol?

Systematic over full-vector RLNC

- Simple
- Less packets to decode the generation
- Improved packet latency
- Lower computational complexity

What about other RLNC schemes?

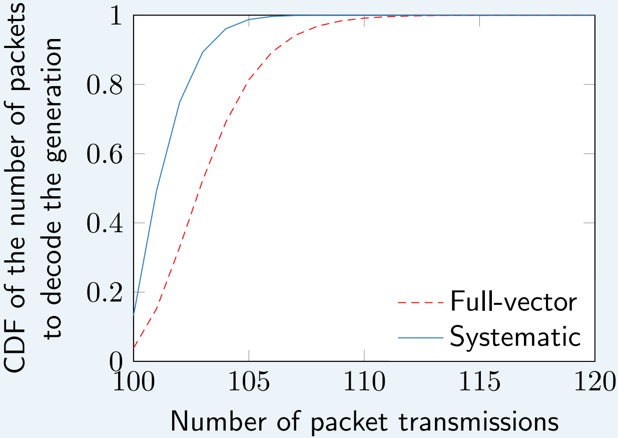
- Sparse: Difficult to model analytically[6]
- Telescopic: Good idea
- Other suggestions?

[6] P. Garrido, D. E. Lucani, and R. Agüero (2017). "Markov Chain Model for the Decoding Probability of Sparse Network Coding". In: *IEEE Trans. Commun.* 65.4, pp. 1675–1685. DOI: 10.1109/TCOMM.2017.2657621.

How better is systematic RLNC?

Less packets to decode the generation

Example for $n = 1$, $q = 2$, $g = 100$, and $\epsilon = 0.02$



How better is systematic RLNC?

Improved packet latency

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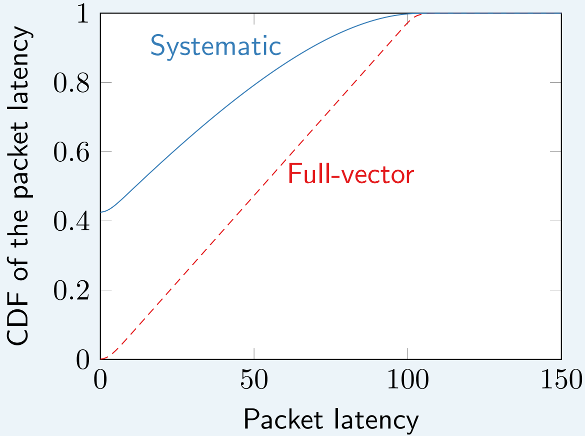

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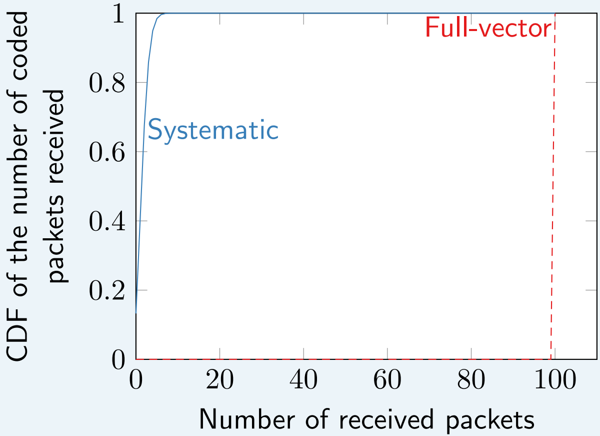

Challenges: Modeling of multicast NCC

Objective

Optimize the performance of the system

Main problem: Correlation of data

1. Multicast problem
2. Multiple sources with different data
   - follow a TDMA schedule
   - include the received packets in the coding matrix

Multicast problem

Exact formulations only exist for the case of one source and two destinations[7]

Lower and upper bounds are used for $n > 2$

This is the most common assumption

$$\Pr\left[\bigcap_{i=1}^{n} X_{t_i}^{(i)} = g\right] = \prod_{i=1}^{n} \Pr\left[X_{t_i}^{(i)} = g\right] \tag{2}$$

[7] E. Tsimbalo, A. Tassi, and R. J. Piechocki (2018). "Reliability of Multicast under Random Linear Network Coding". In: *IEEE Trans. Commun.* to be published.

Multicast problem

Exact formulations only exist for the case of one source and two destinations[7]

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This is the most common assumption, but is not true

$$\Pr\left[\bigcap_{i=1}^{n} X_{t_i}^{(i)} = g\right] \neq \prod_{i=1}^{n} \Pr\left[X_{t_i}^{(i)} = g\right] \qquad (2)$$

[7] E. Tsimbalo, A. Tassi, and R. J. Piechocki (2018). "Reliability of Multicast under Random Linear Network Coding". In: *IEEE Trans. Commun.* to be published.

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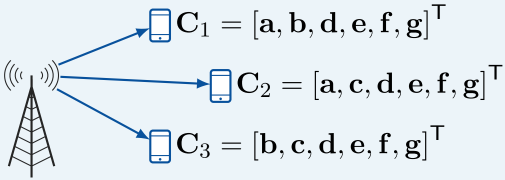
Example: What is the probability that every UE decodes if $g = 5$ and $q = 2$? (Tsimbalo, Tassi, and Piechocki 2018)

Full-vector RLNC



- Real:
- Simple bound:
- Improved bound:

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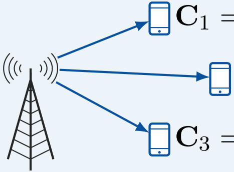


$$\mathbf{C}_1 = [\mathbf{a}, \mathbf{b}, \mathbf{d}, \mathbf{e}, \mathbf{f}, \mathbf{g}]^\mathsf{T}$$

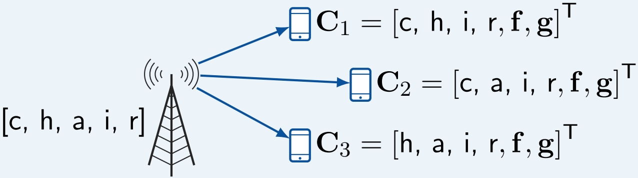
$$\mathbf{C}_2 = [\mathbf{a}, \mathbf{c}, \mathbf{d}, \mathbf{e}, \mathbf{f}, \mathbf{g}]^\mathsf{T}$$

$$\mathbf{C}_3 = [\mathbf{b}, \mathbf{c}, \mathbf{d}, \mathbf{e}, \mathbf{f}, \mathbf{g}]^\mathsf{T}$$

- Real: 0.33
- Simple bound: 0.20
- Improved bound: 0.27

Example: What is the probability that every UE decodes if $g = 5$ and $q = 2$?

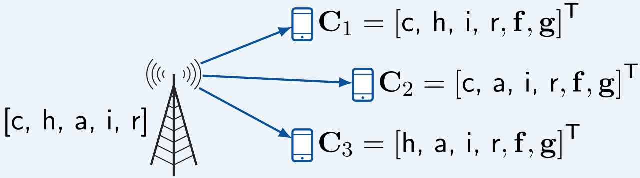
Systematic RLNC



- Real:
- Conditional probability:

Example: What is the probability that every UE decodes if $g = 5$ and $q = 2$?

Systematic RLNC



- Real: 0.42
- Conditional probability: 0.42

Solutions to multicast problem

Systematic RLNC

- It is safe to simply use

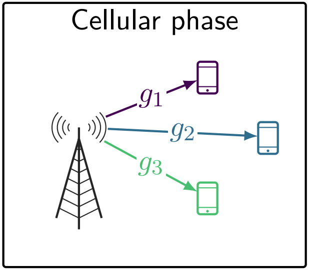
$$\Pr\left[\bigcap_{i=1}^{n} X_{t_i}^{(i)} = g\right] \geq \prod_{i=1}^{n} \Pr\left[X_{t_i}^{(i)} = g\right], \qquad (3)$$

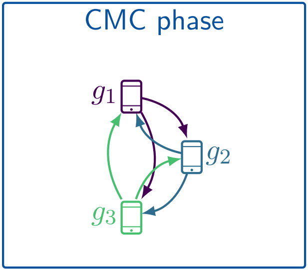
but be aware that it is a lower bound

Multiple sources with different data

The eNB transmits g_i packets to the ith UE

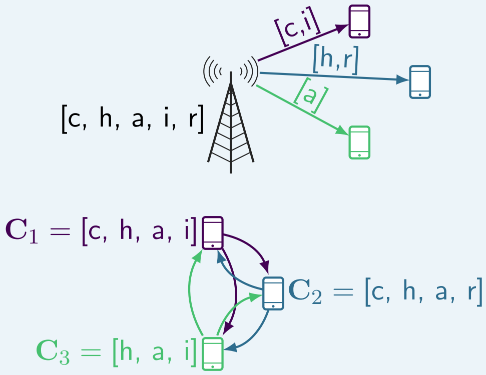
- These are not present at the remaining UEs before the CMC phase
- Is not a problem during non-coded transmissions (Systematic RLNC)





Multiple sources with different data and Systematic RLNC

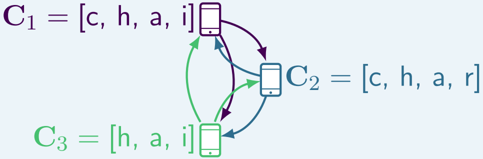
I want to obtain the exact probability that a packet transmitted from j to i is innovative



Multiple sources with different data

What is the exact probability that a packet transmitted from j to i is innovative

$$\mathbb{P}\left(t_i \mid x, z\right) = P\left[X_{t_i+1}^{(i)} = x + 1 \mid X_{t_i}^{(i)} = x \cap Z_{t_i}^{(i,j)} = z\right] \tag{4}$$



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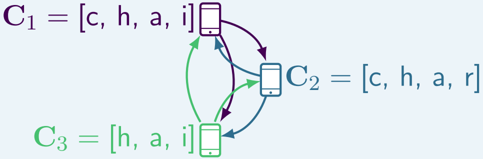

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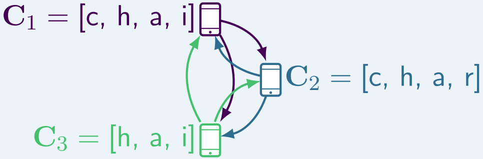

How do I obtain x and z?

Easy, you need the joint pmf of $X^{(i)}_{t_i}$ and $Z^{(i,j)}_{t_i}$

Multiple sources with different data

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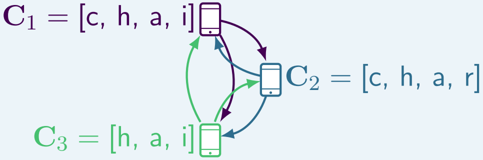
$$\begin{aligned}\mathbb{P}\left(t_i \mid x, z\right) &= P\left[X^{(i)}_{t_i+1} = x+1 \mid X^{(i)}_{t_i} = x \cap Z^{(i,j)}_{t_i} = z\right] \\ &= 1 - q^{x+z-g}.\end{aligned} \tag{4}$$



How do I obtain x and z?

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Multiple sources with different data

Example of $X_0^{(i)}$ and $Z_0^{(i,j)}$ in Pv2 under Systematic RLNC

$$p_{X_0 Z_0}(x, z \mid i, j) = \epsilon^{g-x+z} \sum_u \left[\binom{g_j}{u} \binom{\gamma}{x - g_i - u} \times \binom{\gamma - x + g_i + u}{z} (1-\epsilon)^{\gamma+u-z} \right] \tag{5}$$

where

- $\gamma = g - g_i - g_j$
- $\{u \in \mathbb{Z}_{\geq 0} | \max\{0, x - \gamma - g_i + z\} \leq u \leq \min\{g_j, x - g_i\}\}$ is the number of dofs in i transmitted by j

Protocol variants (Pv and Pv2)

Exact same modeling under the following assumptions

- PER at the LTE-A link $\epsilon_\ell = 0$ (eNB can recover the errors)
- Same PER between UE pairs, $\epsilon_{\{i,j\}} = \epsilon$ for all i and$j$
- Difference: Pv1 only possible if the WiFi data rate is higher than the LTE-A data rate

Rank of the coding matrix of the ith UE

At the end of the cellular phase

$$g_i = \left\lceil \frac{g-(i-1)}{n} \right\rceil \tag{6}$$

At the end of the systematic transmissions

$$p_{X_0}(x;i) = \Pr\left[X_0^{(i)} = x\right] = \binom{g-g_i}{x-g_i} (1-\epsilon)^{x-g_i}\, \epsilon^{g-x} \tag{7}$$

Multiple sources with different data problem

For $t_i > 0$ coded packets are transmitted, so we go back to our problem

$$p_{X_0 Z_0}(x, z \mid i, j) = \epsilon^{g-x+z} \sum_u \left[\binom{g_j}{u} \binom{\gamma}{x - g_i - u} \times \binom{\gamma - x + g_i + u}{z} (1-\epsilon)^{\gamma+u-z} \right] \tag{8}$$

Solution: Simplify the problem

What if we just assume $\Pr\left[Z_{t_i}^{(i,j)} = 0\right] = 1$ for all t_i?

- We can define

$$\mathbb{P}'(t_i) = \mathbb{P}\left(t_i \mid x, 0\right) = 1 - q^{x-g} \tag{9}$$

- We can use the pmf of $X_{t_i}^{(i)}$ alone instead of the joint pmf of $X_{t_i}^{(i)}$ and $Z_{t_i}^{(i,j)}$

Accuracy of our simplification

Mean squared error (MSE) between the approximate and exact probability that the first coded transmission is innovative.

	$n = 3$		$n = 100$	
	$g = 10$	$g = 100$	$g = 10$	$g = 100$
$\epsilon = 0.02$				
$q = 2$	$2.85 \cdot 10^{-4}$	$1.71 \cdot 10^{-3}$	$9.13 \cdot 10^{-4}$	$3.64 \cdot 10^{-3}$
$q = 2^8$	$4.22 \cdot 10^{-6}$	$1.39 \cdot 10^{-5}$	$1.30 \cdot 10^{-5}$	$2.12 \cdot 10^{-5}$
$\epsilon = 0.16$				
$q = 2$	$1.25 \cdot 10^{-2}$	$8.38 \cdot 10^{-4}$	$2.92 \cdot 10^{-2}$	$1.29 \cdot 10^{-4}$
$q = 2^8$	$1.25 \cdot 10^{-4}$	$4.12 \cdot 10^{-8}$	$2.82 \cdot 10^{-4}$	$3.96 \cdot 10^{-10}$

Probability of decoding given at the ith UE given t_i

Same as in a unicast session for each i

$$F_T\left(t_i; i\right) = F_{X_{t_i}}\left(g; i\right) = \Pr\left[X_{t_i}^{(i)} = g\right] \tag{10}$$

$$F_{T|X_0}\left(t_i \mid x; i\right) = \sum_{u=g-x}^{t_i} \binom{t_i}{u} \left(1-\epsilon\right)^u \epsilon^{t_i - u} F_{\mathsf{rlnc}}\left(u; g-x\right) \tag{11}$$

$$F_T\left(t_i; i\right) = \sum_{x=g_i}^{g} p_{X_0}\left(x; i\right) F_{T|X_0}\left(t_i \mid x; i\right) \tag{12}$$

How many transmissions are needed to decode with a certain reliability?

t_i depends on the number of total coded transmissions, s

$$t_i = f(s,i) = s + g_i - \left\lceil \frac{g + s - (i-1)}{n} \right\rceil \tag{13}$$

Then we go back to the multicast problem

$$F_S\left(s;n\right) \equiv \Pr\left[\bigcap_{i=1}^{n} X_{f(s,i)}^{(i)} = g\right], \tag{14}$$

which we simplify

$$F_S'\left(s;n\right) = \prod_{i=1}^{n} \Pr\left[X_{f(s,i)}^{(i)} = g\right] = \prod_{i=1}^{n} F_T\left(f(s,i);i\right) \tag{15}$$

How many transmissions are needed to decode with a certain reliability?

t_i depends on the number of total coded transmissions, s

$$t_i = f(s,i) = s + g_i - \left\lceil \frac{g + s - (i-1)}{n} \right\rceil \tag{13}$$

Then we go back to the multicast problem

$$F_S(s;n) \equiv \Pr\left[\bigcap_{i=1}^{n} X^{(i)}_{f(s,i)} = g\right], \tag{14}$$

which we simplify again?

$$F'_S(s;n) = \prod_{i=1}^{n} \Pr\left[X^{(i)}_{f(s,i)} = g\right] = \prod_{i=1}^{n} F_T\left(f(s,i);i\right) \tag{15}$$

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which we simplify again? yes, again!

$$F_S'\left(s;n\right) = \prod_{i=1}^{n} \Pr\left[X_{f(s,i)}^{(i)} = g\right] = \prod_{i=1}^{n} F_T\left(f(s,i);i\right) \tag{15}$$

Now we obtain:

Optimal number of time slots allocated for coded transmissions to achieve the desired reliability, τ

$$s^* \equiv \min_s \left\{ s \mid F'_S\left(s; n\right) \geq \tau \right\} \tag{16}$$

Throughput given the LTE-A data rate, R

$$R_{\mathsf{ue}}(n) = \frac{\ell}{d_s} \frac{g}{2g + s^*} = R \frac{g}{2g + s^*} \tag{17}$$

Now we obtain:

Average energy consumption given the power consumption, $P_{\text{cel,rx}}$[8], $P_{\text{wifi,rx}}$, and $P_{\text{wifi,tx}}$[9]

$$\overline{E}_{\text{cmc}}(n) = \frac{1}{d_s}\left[g\,P_{\text{cel,rx}} + (g + s^*)\,P_{\text{wifi,tx}} + \left(n\,g + \sum_{i=1}^{n} \mathbb{E}\left[T^{(i)} \mid s^*\right] - g_i\right) P_{\text{wifi,rx}}\right]; \quad (18)$$

[8] Mads Lauridsen et al. (2014). "An empirical LTE smartphone power model with a view to energy efficiency evolution". In: *Intel® Technol. J.* 18.1, pp. 172–193.

[9] L. Sun et al. (2017). "Experimental Evaluation of WiFi Active Power/Energy Consumption Models for Smartphones". In: *IEEE Trans. Mobile Comput.* 16.1, pp. 115–129. ISSN: 1536-1233. DOI: 10.1109/TMC.2016.2538228.

Parameter settings

Parameter	Symbol	Settings
Generation size	g	100 packets
Field size	q	$\{2, 2^8\}$
Cloud size	n	$\{2, 3, \ldots, 100\}$
Packet erasure rate (PER)	ϵ	$\{0.2, 0.4, 0.8, 0.16\}$
Subframe duration	d_s	1 ms
Packet length	ℓ	1470 bytes
Data rate at the LTE-A and WiFi links	R	11.76 Mbps
Power cons. for LTE-A reception	$P_{\text{cel,rx}}$	924.57 mW
Power cons. for WiFi transmission	$P_{\text{wifi,tx}}$	235.20 mW
Power cons. for WiFi reception	$P_{\text{wifi,rx}}$	235.20 mW

Results

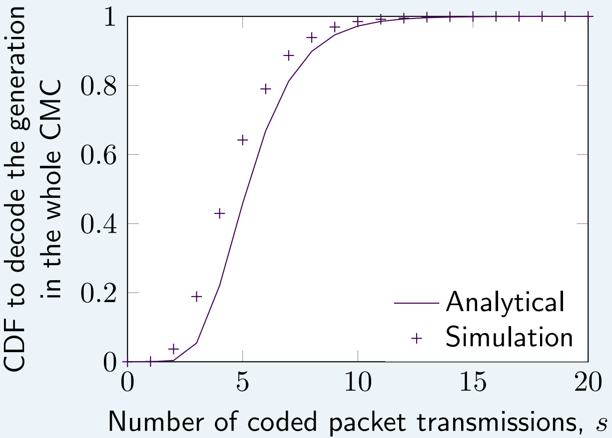
How big is the MSE in the pmf of S of our model vs a "hausgemachter" simulator?

	$n = 3$		$n = 100$	
	$g = 10$	$g = 100$	$g = 10$	$g = 100$
$\epsilon = 0.02$				
$q = 2$	$9.15 \cdot 10^{-6}$	$2.02 \cdot 10^{-6}$	$2.85 \cdot 10^{-3}$	$2.59 \cdot 10^{-4}$
$q = 2^8$	$6.54 \cdot 10^{-5}$	$7.43 \cdot 10^{-6}$	$2.81 \cdot 10^{-5}$	$4.21 \cdot 10^{-6}$
$\epsilon = 0.16$				
$q = 2$	$3.29 \cdot 10^{-5}$	$8.44 \cdot 10^{-6}$	$5.56 \cdot 10^{-4}$	$1.30 \cdot 10^{-4}$
$q = 2^8$	$1.50 \cdot 10^{-4}$	$1.25 \cdot 10^{-5}$	$2.88 \cdot 10^{-5}$	$2.41 \cdot 10^{-5}$

Results

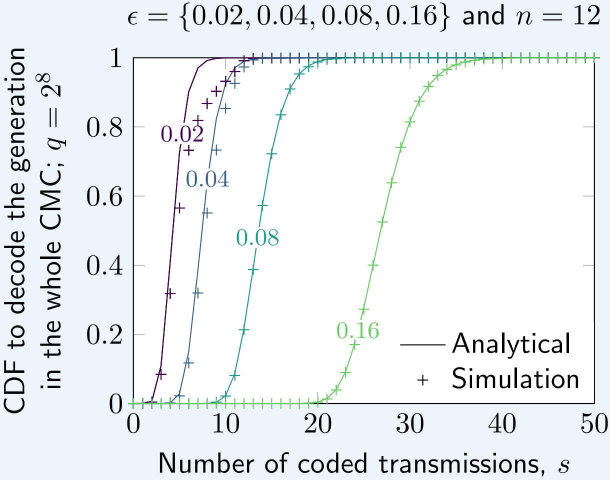
Our model vs "hausgemachter" simulator; worst case

$\epsilon = \{0.02\}$, $q = 2$, $g = 10$, and $n = 100$



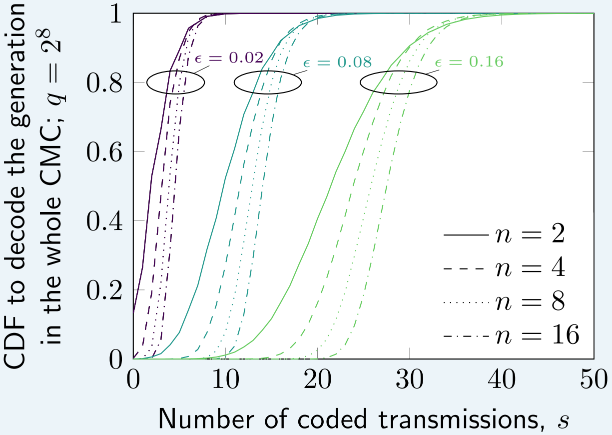
Results

Our model vs KODO: different conditions



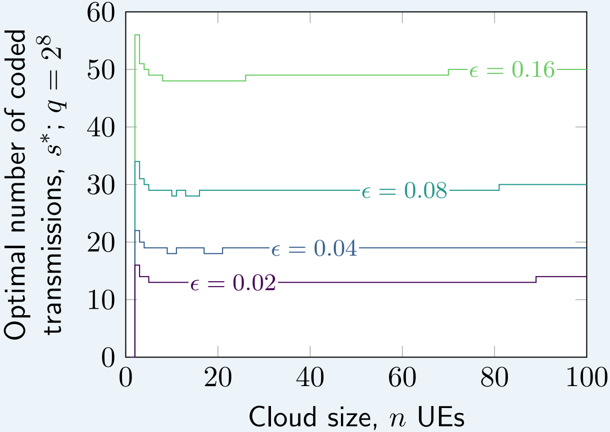
Results

How does n affects performance?



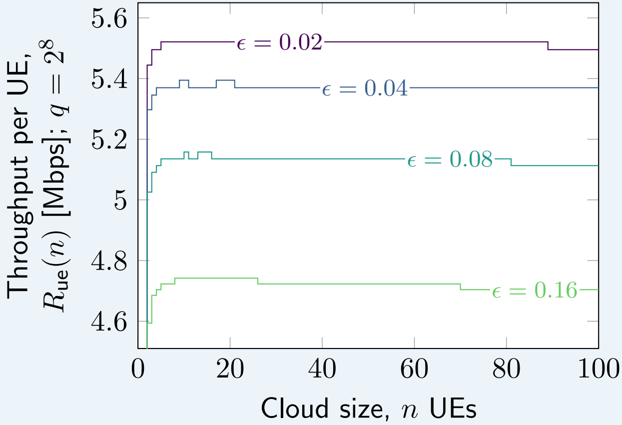
Results

How does n affects performance?



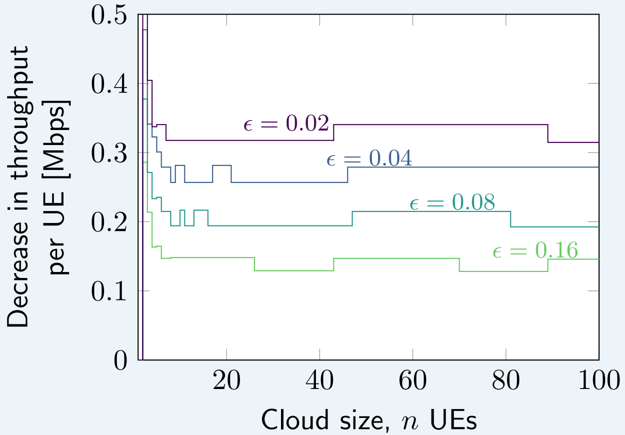
Results

How does n affects throughput?



Results

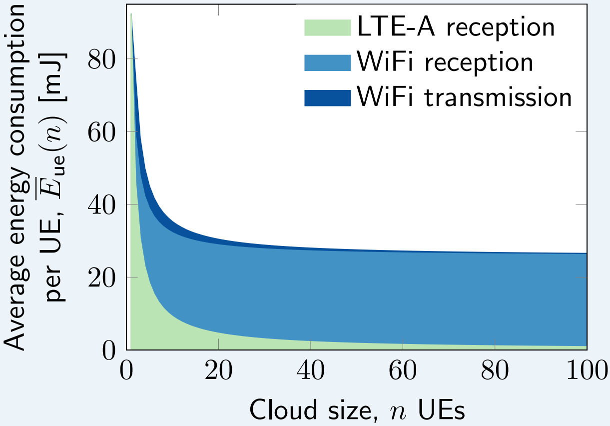
How does $q = 2$ affects throughput when compared to $q = 2^8$?



Results

What are the energy gains of NCC?

$q = 2^8$ and $\epsilon = 0.16$



Future work

Improved model

- Recursive approximation for the joint pmf of $X_{t_i}^{(i)}$ and $Z_{t_i}^{(i,j)}$ for all t_i
- Adapt for a practical implementation with KODO
- Consider energy consumption during decoding

RLNC

- Include other "flavors" or RLNC

Paper submissions

- Conference paper to GLOBECOM 2018
- Extension to a Q1 journal

Thanks for your attention

Any questions?

- Proposed protocol
- LTE-A
- Modeling
- Other topics:
  - Former and current areas of research (e.g., RA protocols, WSNs, NB-IoT)
  - New lines of research
  - Personal (e.g., grants)

Thanks for your attention

Any questions?

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- Other topics:
  - Former and current areas of research (e.g., RA protocols, WSNs, NB-IoT)
  - New lines of research
  - Personal (e.g., grants)
- Further questions: isleyma@upv.es

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