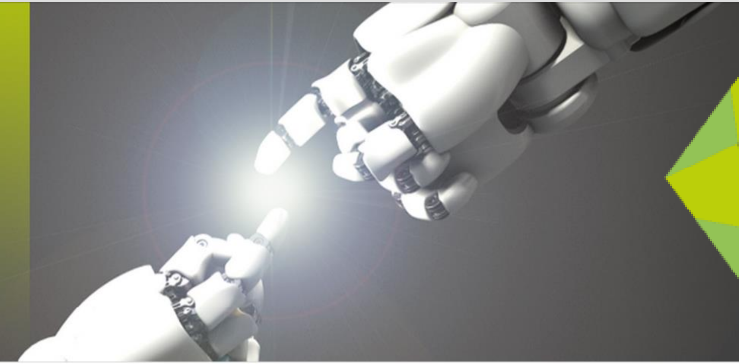
TECHNISCHE UNIVERSITÄT DRESDEN



Real World Network Coding

5G LAB GERMANY

Frank Fitzek **Communications Networks**

Steinwurf Chocolate Cloud codeon

coordinator

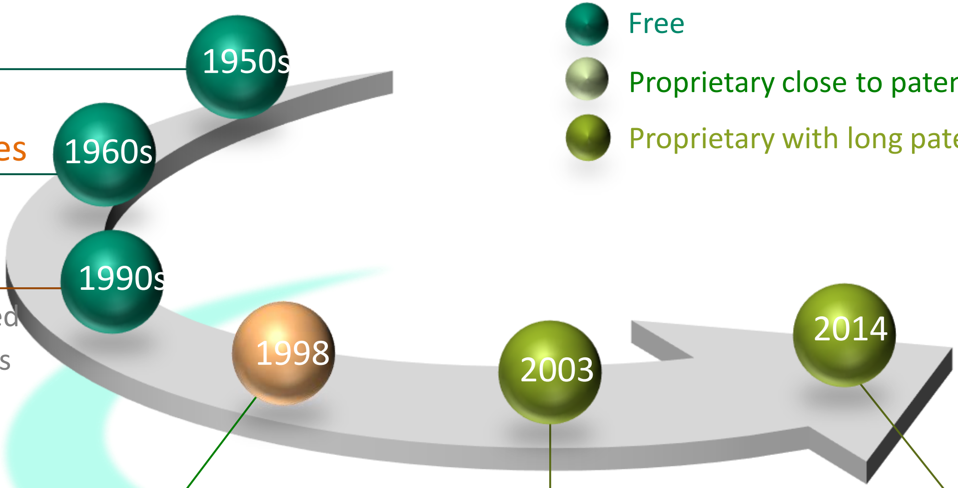
serial entrepreneur

Alcatel·Lucent CLAAS ERICSSON NATIONAL INSTRUMENTS NOKIA ROHDE&SCHWARZ vodafone

Evolution of Coding

5G LAB GERMANY

- Free
- Proprietary close to patent expiry
- Proprietary with long patent life



Block Codes

Convolutional Codes

Modern Codes

- LDPCs – patent expired
- Turbo Codes – patents expired or expiring

Rateless Codes

Raptor and related codes

- Rate-less (refinement to free E2E)
- Still E2E, still static

Network Codes codeon

- RLNC enables network coding
- Deterministic construction for special cases
  - Index Coding
  - CATWOMAN (Linux 3.10)

Fulcrum Codes codeon

- RLNC-enabled Steinwurf
  - *Fluid complexity* (flexible field size)
  - Breaks performance-overhead trade-off

Random Linear Network Coding

Orignal packets

$$\begin{pmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \end{pmatrix} = \begin{pmatrix} \alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} & \alpha_{1,4} & \alpha_{1,5} & \alpha_{1,6} \\ \alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3} & \alpha_{2,4} & \alpha_{2,5} & \alpha_{2,6} \\ \alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3} & \alpha_{3,4} & \alpha_{3,5} & \alpha_{3,6} \\ \alpha_{4,1} & \alpha_{4,2} & \alpha_{4,3} & \alpha_{4,4} & \alpha_{4,5} & \alpha_{4,6} \\ \alpha_{5,1} & \alpha_{5,2} & \alpha_{5,3} & \alpha_{5,4} & \alpha_{5,5} & \alpha_{5,6} \\ \alpha_{6,1} & \alpha_{6,2} & \alpha_{6,3} & \alpha_{6,4} & \alpha_{6,5} & \alpha_{6,6} \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \end{pmatrix}$$

Gaussian elimination *n* x *n matrix* requires $An^3 + Bn^2 + Cn$ operations.

Random Linear Network Coding

coding
coefficients

$$\begin{pmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \end{pmatrix} = \begin{pmatrix} \alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} & \alpha_{1,4} & \alpha_{1,5} & \alpha_{1,6} \\ \alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3} & \alpha_{2,4} & \alpha_{2,5} & \alpha_{2,6} \\ \alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3} & \alpha_{3,4} & \alpha_{3,5} & \alpha_{3,6} \\ \alpha_{4,1} & \alpha_{4,2} & \alpha_{4,3} & \alpha_{4,4} & \alpha_{4,5} & \alpha_{4,6} \\ \alpha_{5,1} & \alpha_{5,2} & \alpha_{5,3} & \alpha_{5,4} & \alpha_{5,5} & \alpha_{5,6} \\ \alpha_{6,1} & \alpha_{6,2} & \alpha_{6,3} & \alpha_{6,4} & \alpha_{6,5} & \alpha_{6,6} \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \end{pmatrix}$$

Gaussian elimination n x n *matrix* requires $An^3 + Bn^2 + Cn$ operations.

Random Linear Network Coding

coded packets

$$\begin{pmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \end{pmatrix} = \begin{pmatrix} \alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} & \alpha_{1,4} & \alpha_{1,5} & \alpha_{1,6} \\ \alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3} & \alpha_{2,4} & \alpha_{2,5} & \alpha_{2,6} \\ \alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3} & \alpha_{3,4} & \alpha_{3,5} & \alpha_{3,6} \\ \alpha_{4,1} & \alpha_{4,2} & \alpha_{4,3} & \alpha_{4,4} & \alpha_{4,5} & \alpha_{4,6} \\ \alpha_{5,1} & \alpha_{5,2} & \alpha_{5,3} & \alpha_{5,4} & \alpha_{5,5} & \alpha_{5,6} \\ \alpha_{6,1} & \alpha_{6,2} & \alpha_{6,3} & \alpha_{6,4} & \alpha_{6,5} & \alpha_{6,6} \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \end{pmatrix}$$

Gaussian elimination *n* x *n matrix* requires $An^3 + Bn^2 + Cn$ operations.

Random Linear Network Coding

$$\begin{pmatrix} C_1 \\ \vdots \\ C_G \\ C_{G+1} \\ \vdots \\ C_K \end{pmatrix} = \begin{pmatrix} \alpha_{1,1} & \cdots & \alpha_{1,G} \\ \vdots & \ddots & \vdots \\ \alpha_{G,1} & \cdots & \alpha_{G,G} \\ \alpha_{G+1,1} & \cdots & \alpha_{G+1,G} \\ \vdots & \ddots & \vdots \\ \alpha_{K,1} & \cdots & \alpha_{K,G} \end{pmatrix} \begin{pmatrix} P_1 \\ \vdots \\ P_G \end{pmatrix}$$

Rateless code: can output any number of coded packets.
(such as Fountain codes, but better than RS)

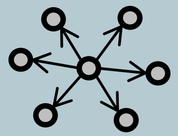
RLNC: The Technology

Coding Today

(all End-to-End)

Classical

Multicast

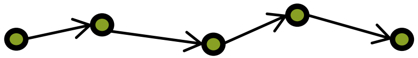


Coding Tomorrow with RLNC

Classical + Sliding Window Encoding

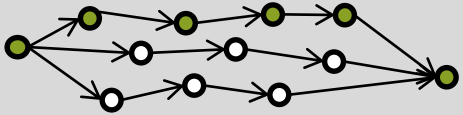
Real time video streaming, TCP, SDN…

Multihop



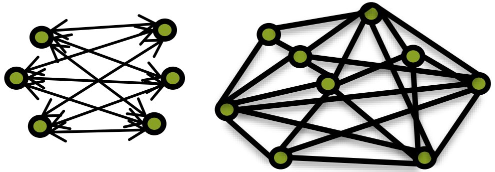
Edge caches, wireless mesh, reliable multicast, satellites, small relay topologies, SDN…

Multipath



Multi-source streaming Multipath TCP, channel bundling, heterogeneous network combining, SDN…

Multisource – Multi-destination / Mesh



Distributed cloud, SDN, advanced mesh (IoT, car2car, M2M, smart grid) …

5G MULTICAST

5G LAB GERMANY

Norm – Reliable Multicast

Reliable Multicast

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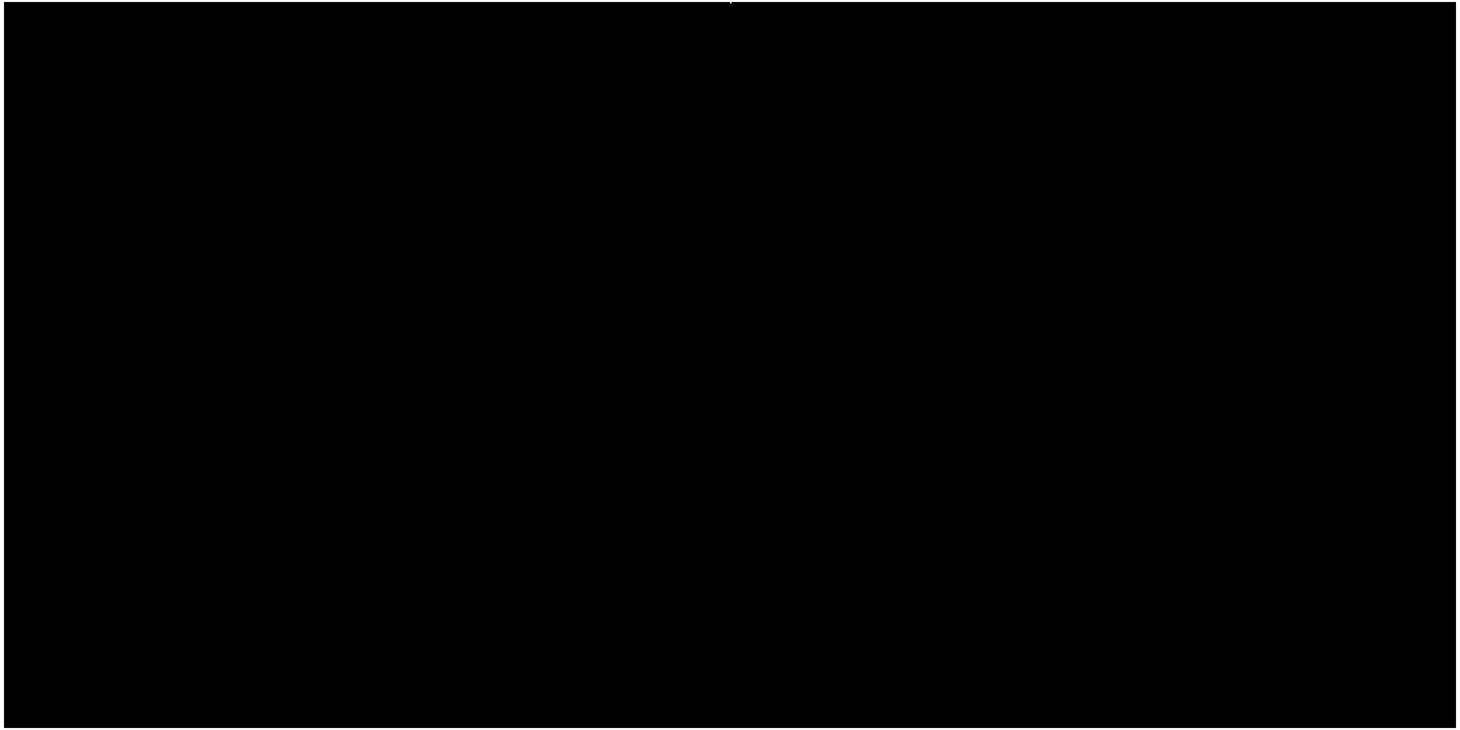
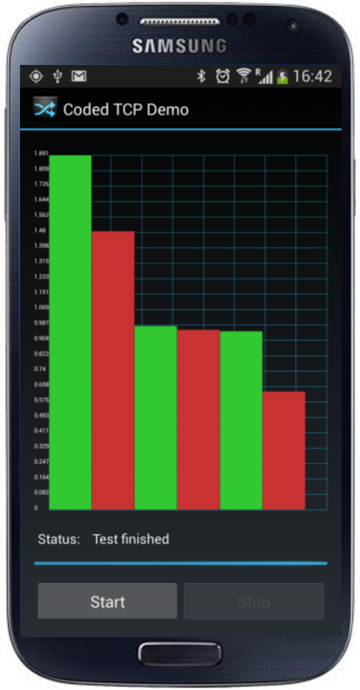
5G CODED POINT TO POINT

Sliding Window



Coded TCP



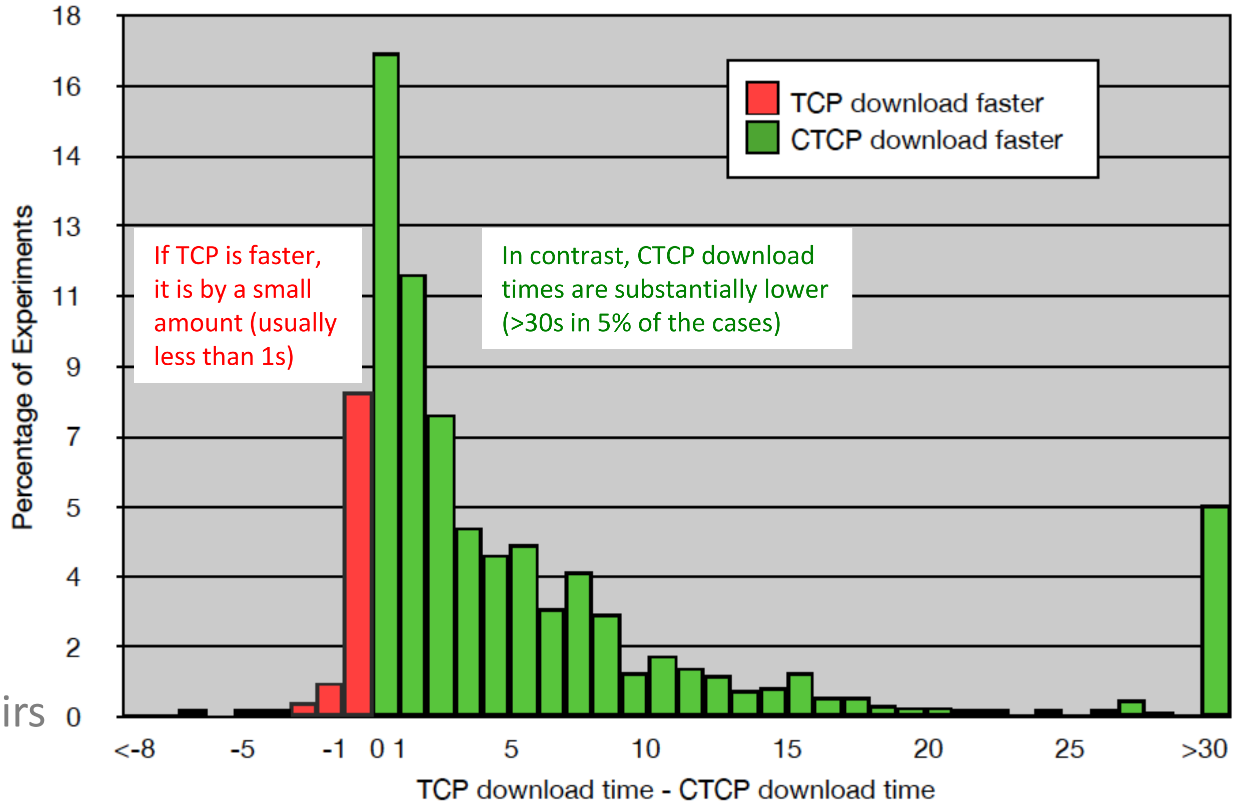
German
y

Irland

US East
Coast

US West
Coast

Histogram of CTCP-TCP Data Pairs



1354 data pairs

Pacific Island Testbed

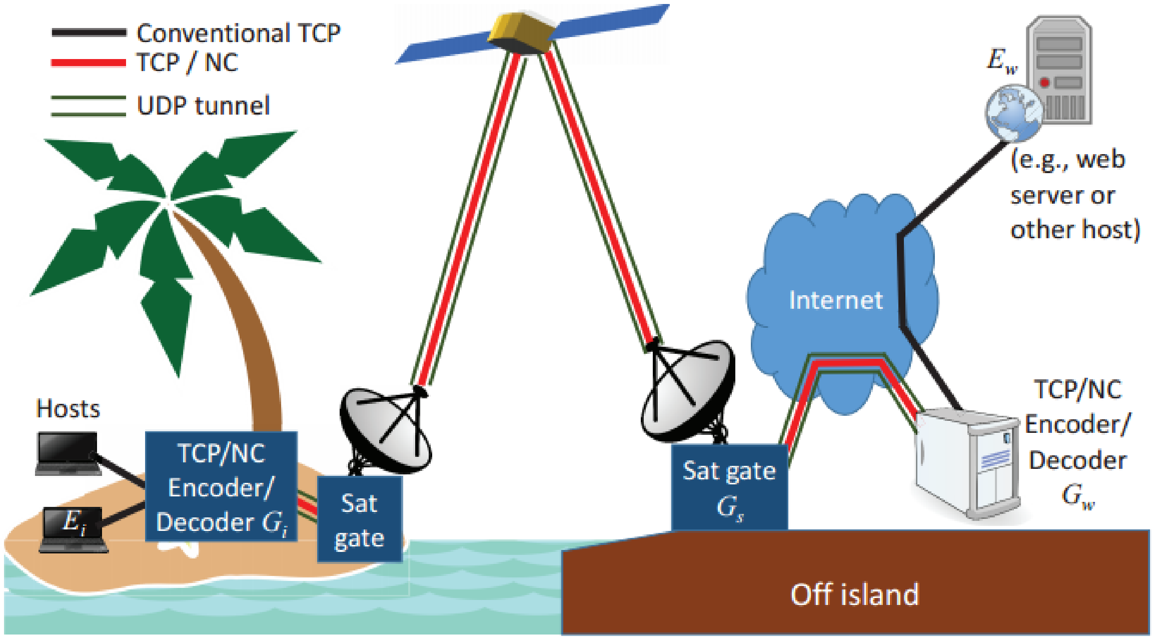
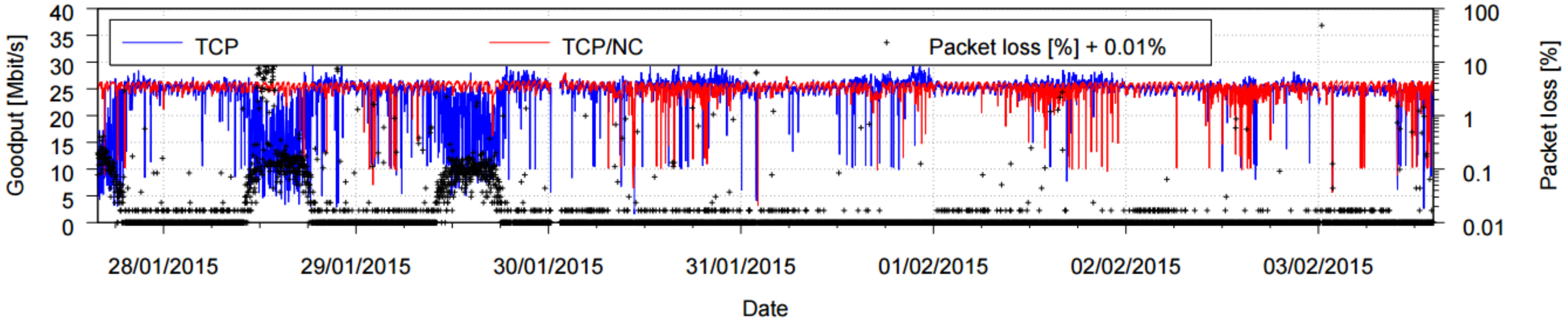
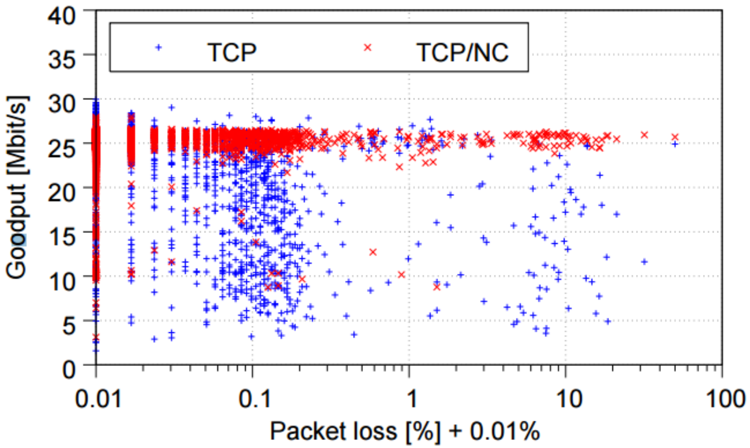


Fig. 1. TCP/NC network topology

http://arxiv.org/pdf/1506.01048v1.pdf

Pacific Island Testbed



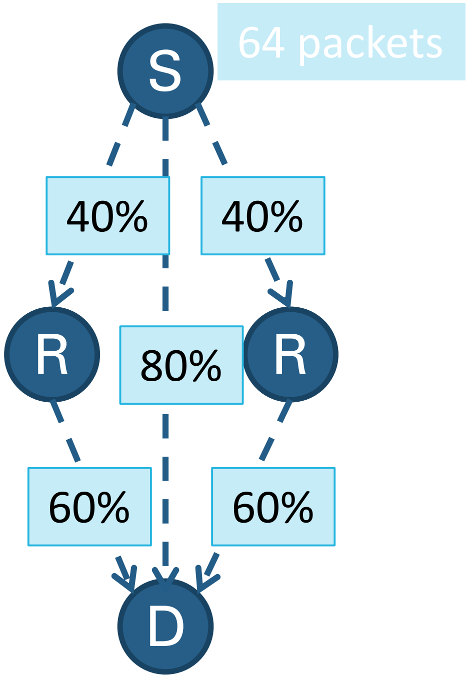


5G WIRELESS MESH

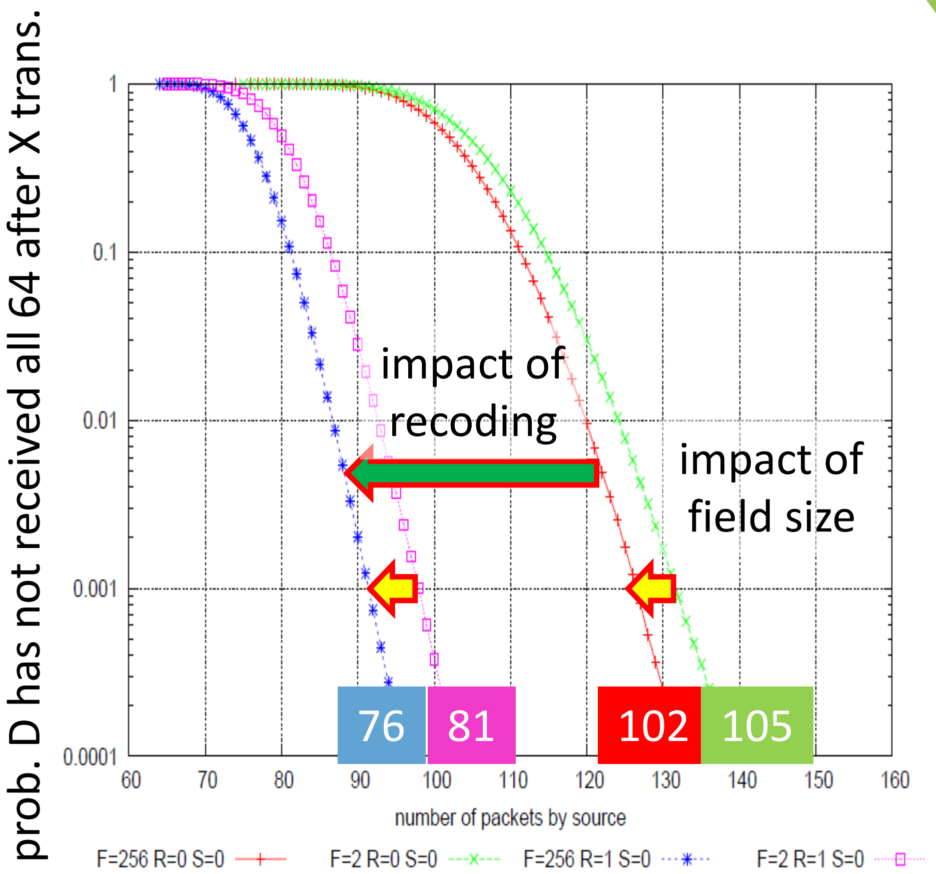
Wireless Mesh

Foto: Torsten Proß, Jeibmann Photographik

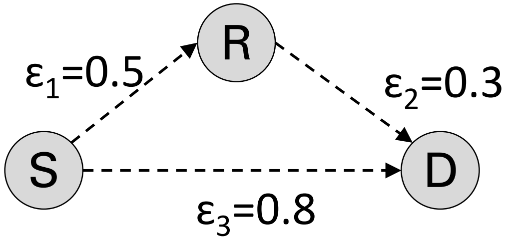
Recoding

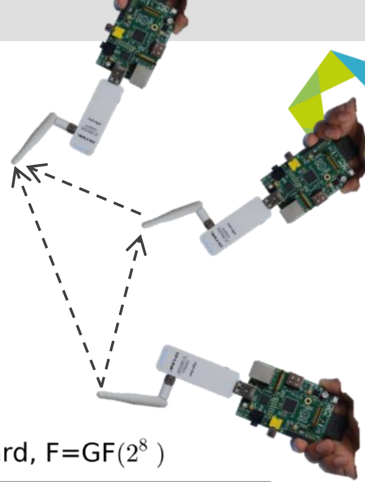


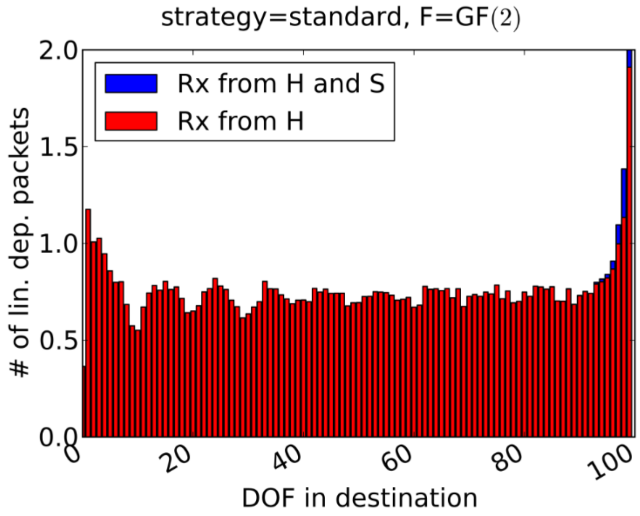
No need for signalling!

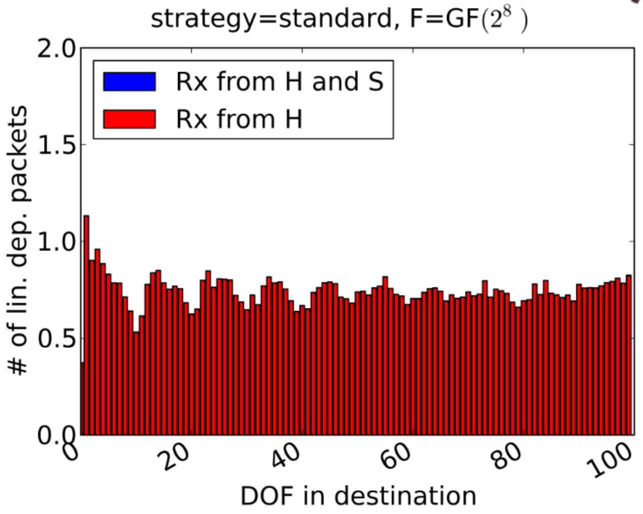


Agnostic Recoding









Recode + Simple Protocol

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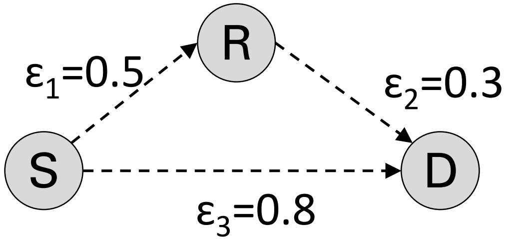
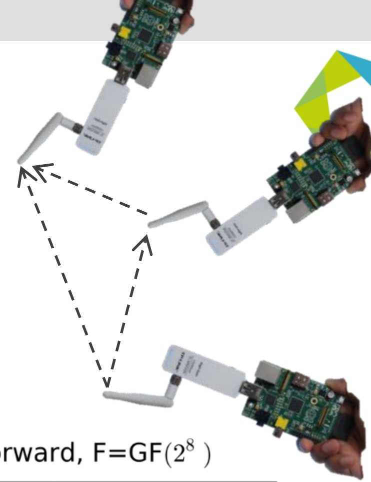
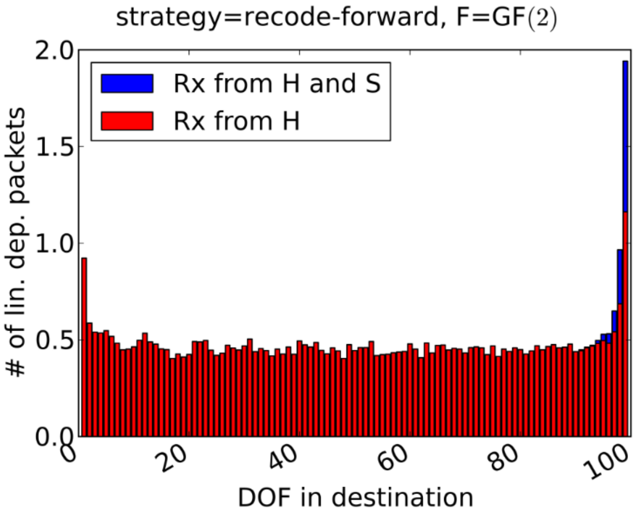
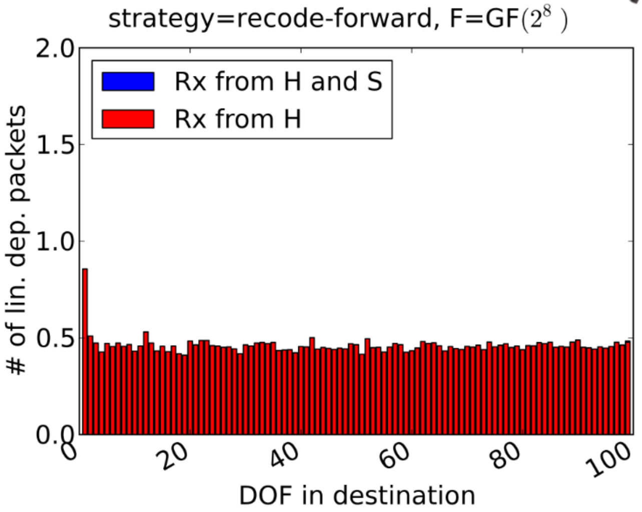
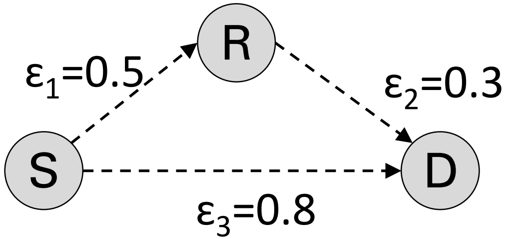


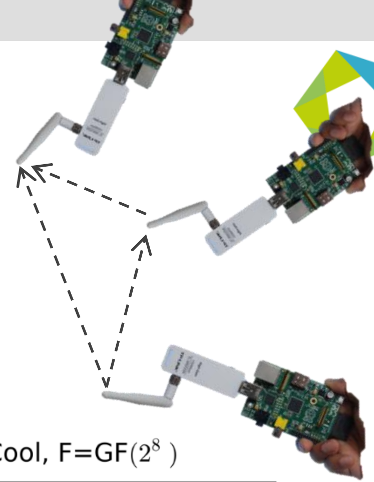


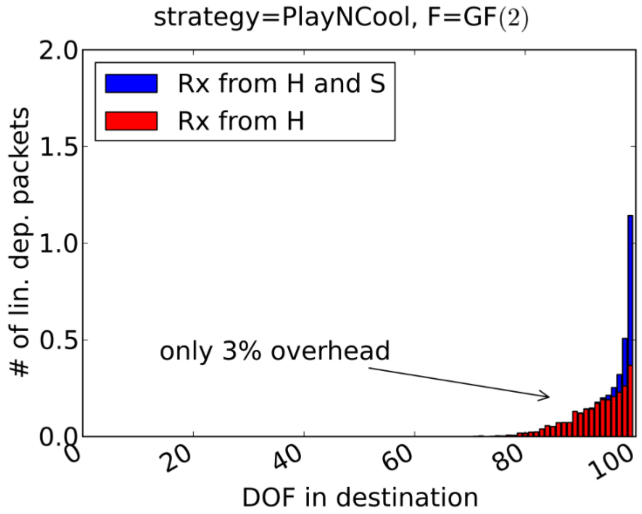


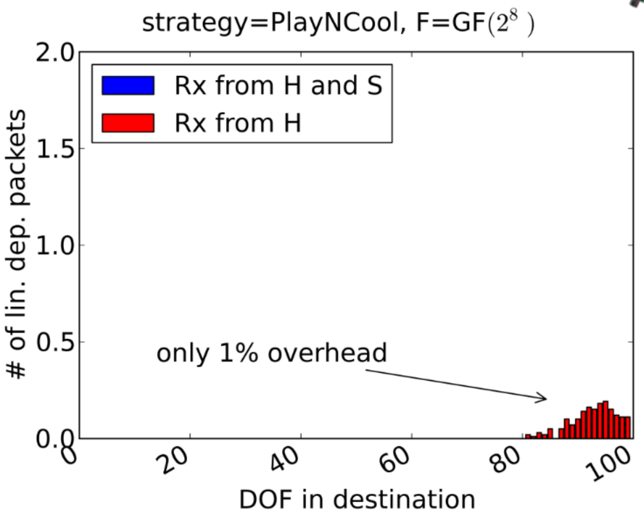


PlayNCool

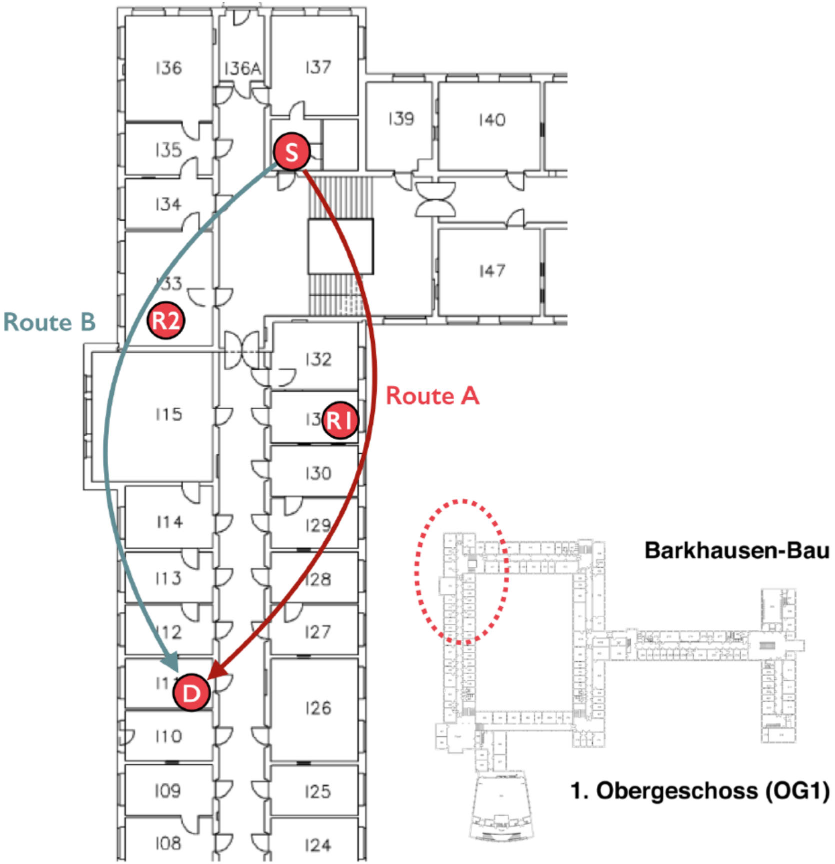

R
S
D
ε1=0.5
ε2=0.3
ε3=0.8

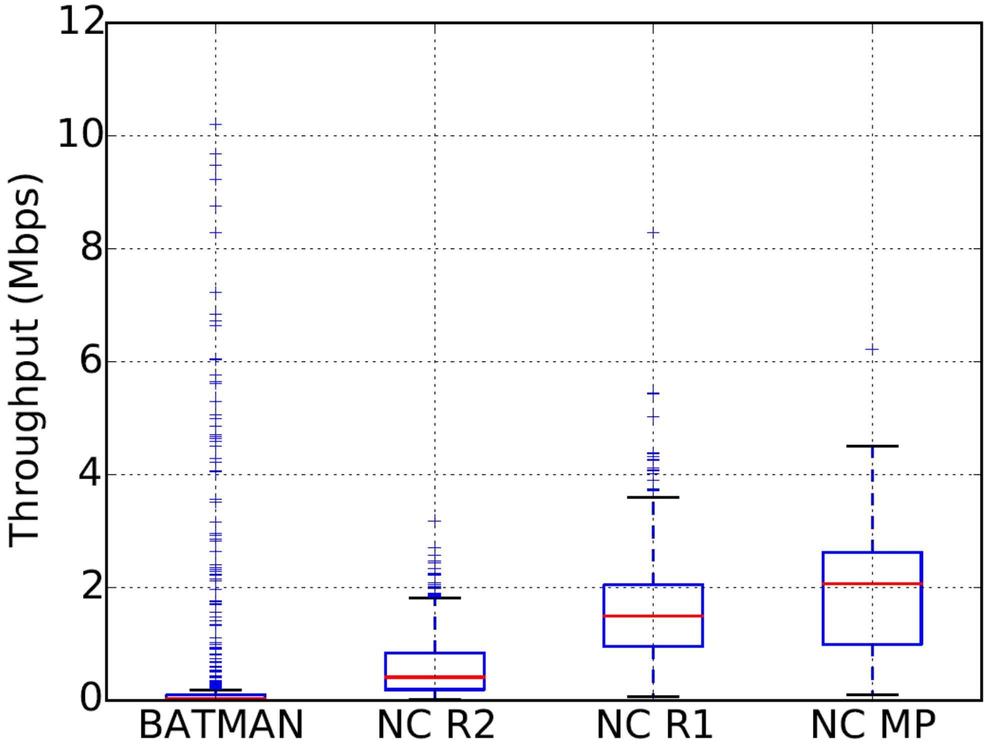



strategy=PlayNCool, F=GF(2)
Rx from H and S
Rx from H
only 3% overhead
# of lin. dep. packets
DOF in destination
0.0
0.5
1.0
1.5
2.0
0
20
40
60
80
100


strategy=PlayNCool, F=GF(2^8)
Rx from H and S
Rx from H
only 1% overhead
# of lin. dep. packets
DOF in destination
0.0
0.5
1.0
1.5
2.0
0
20
40
60
80
100

Some Real Stuff

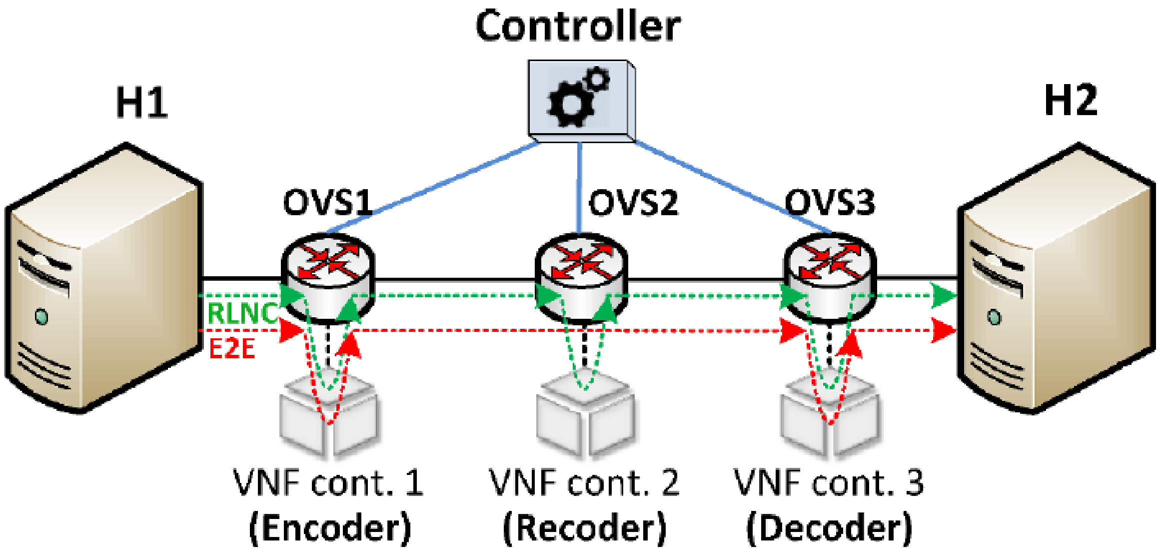




5G SOFTWARE DEFINED NETWORK

5G LAB GERMANY

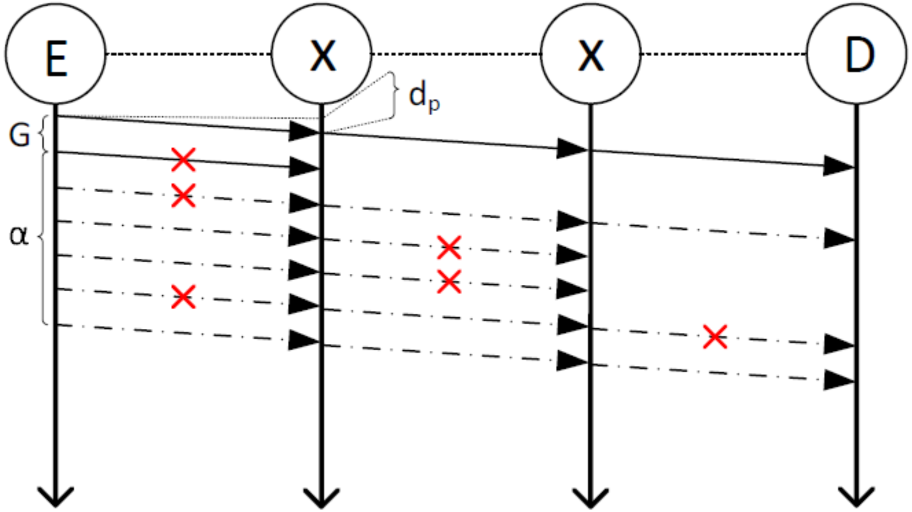
Virtual SDN testbed



Software Defined Networks

End to End Coding Schemes: Store and Forward

$$P_{E2E} = \sum_{h=1}^{H} G \cdot \left(\frac{1}{(1-\epsilon)^h} \right) \qquad D_{E2E} = (G \cdot \left(\frac{1}{(1-\epsilon)^H} \right) + (H-1)) \cdot d_p$$

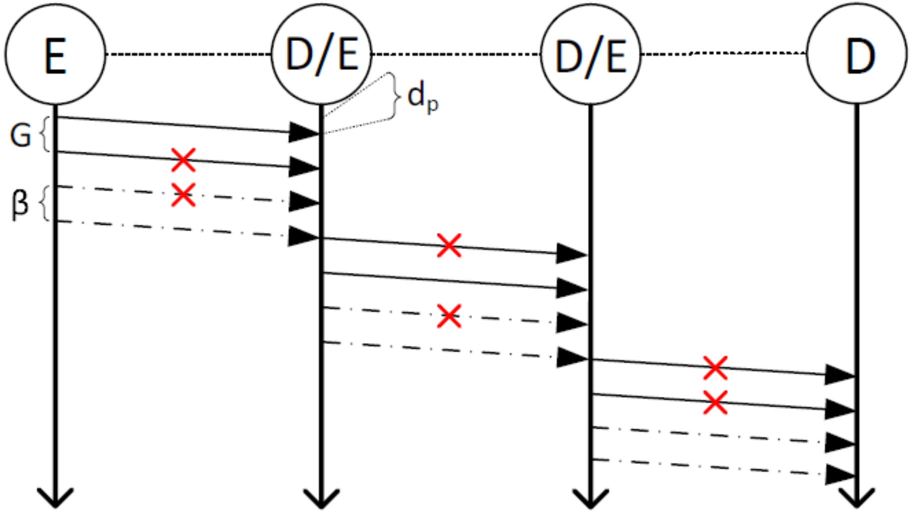


Software Defined Networks

Hop by Hop Coding Scheme: Store and Forward

$$P_{HbH} = G \cdot H \cdot \left(\frac{1}{1-\epsilon}\right)$$

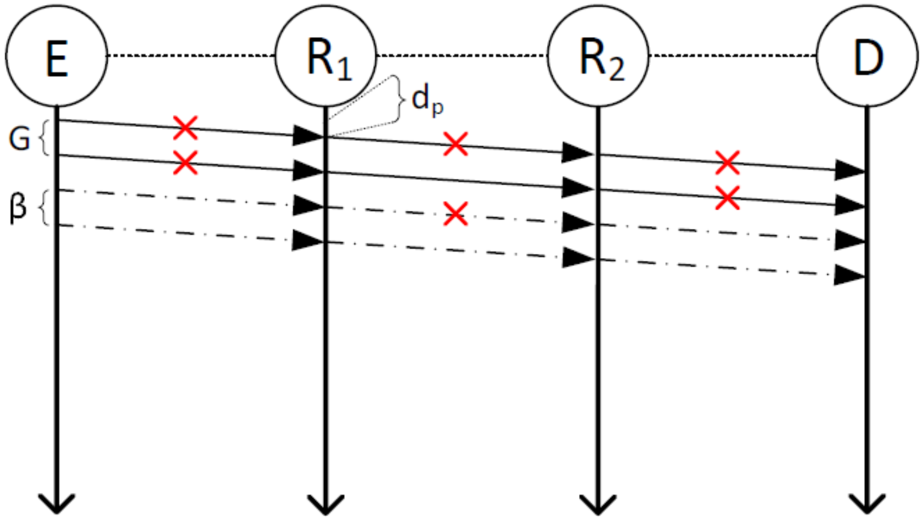
$$D_{HbH} = G \cdot \left(\frac{1}{1-\epsilon}\right) \cdot H \cdot d_p$$



Software Defined Networks

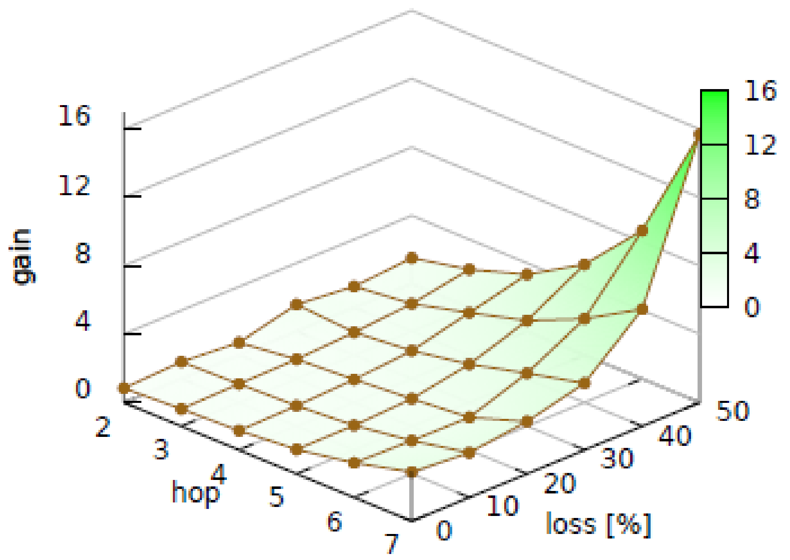
Network Coding Scheme: Compute and Forward

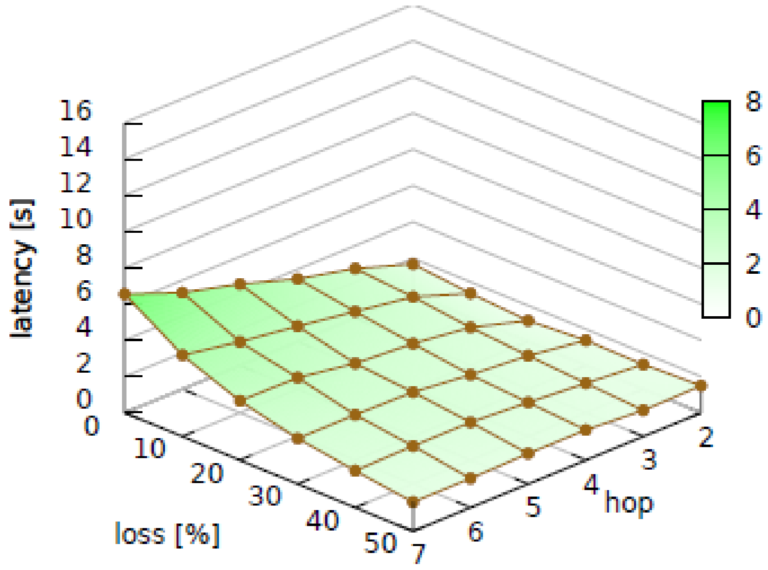
$$P_{RLNC} = G \cdot H \cdot \left(\frac{1}{1-\epsilon}\right) \qquad D_{RLNC} = \left(G \cdot \left(\frac{1}{1-\epsilon}\right) + (H-1)\right) \cdot d_p$$



Software Defined Networks

Latency gain of e2e vs RLNC (left) and hbh vs RLNC(right)



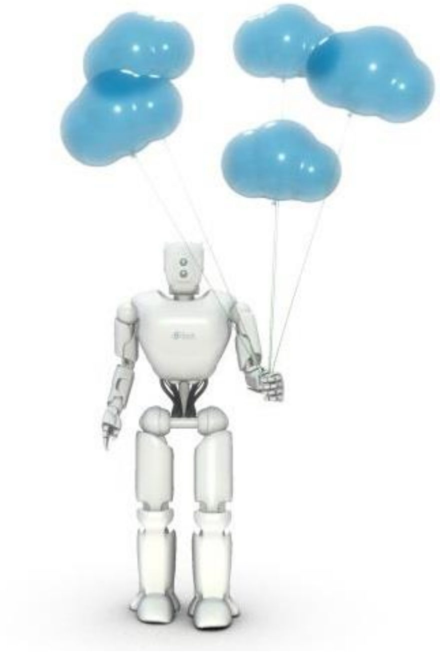


5G LAB GERMANY

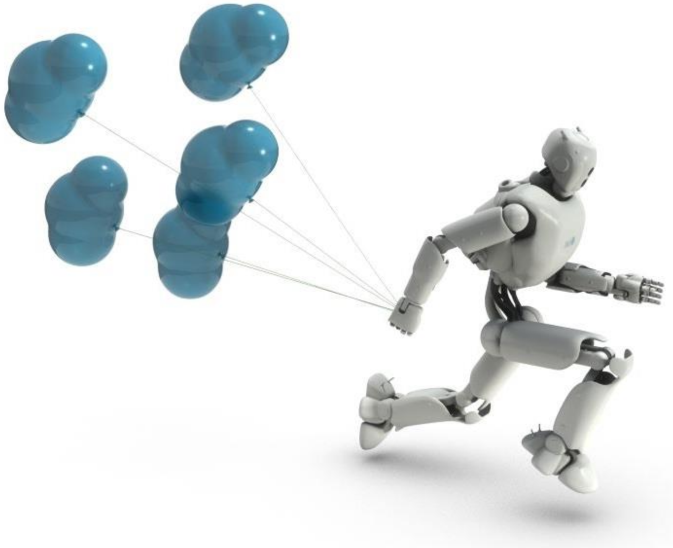
5G AGILE CLOUD

Cloud Evolution

Single/Static



Distributed/Static

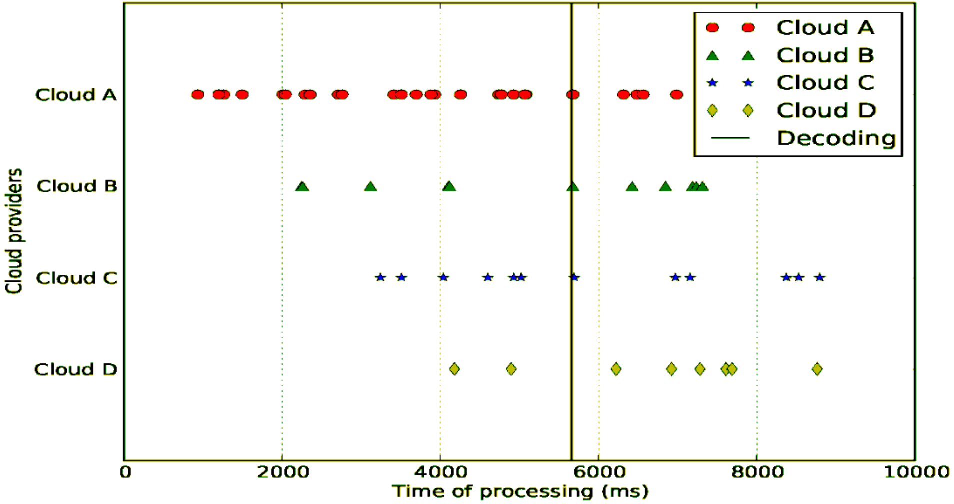


Distributed/Agile

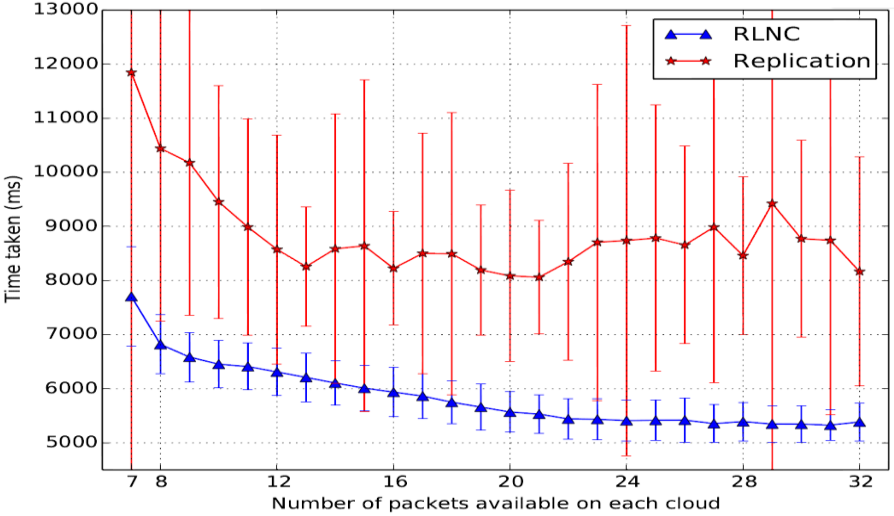
Example: Distributed Cloud

Example: Distributed Cloud

- Heterogenity (4 clouds)
- Clouds behave differently

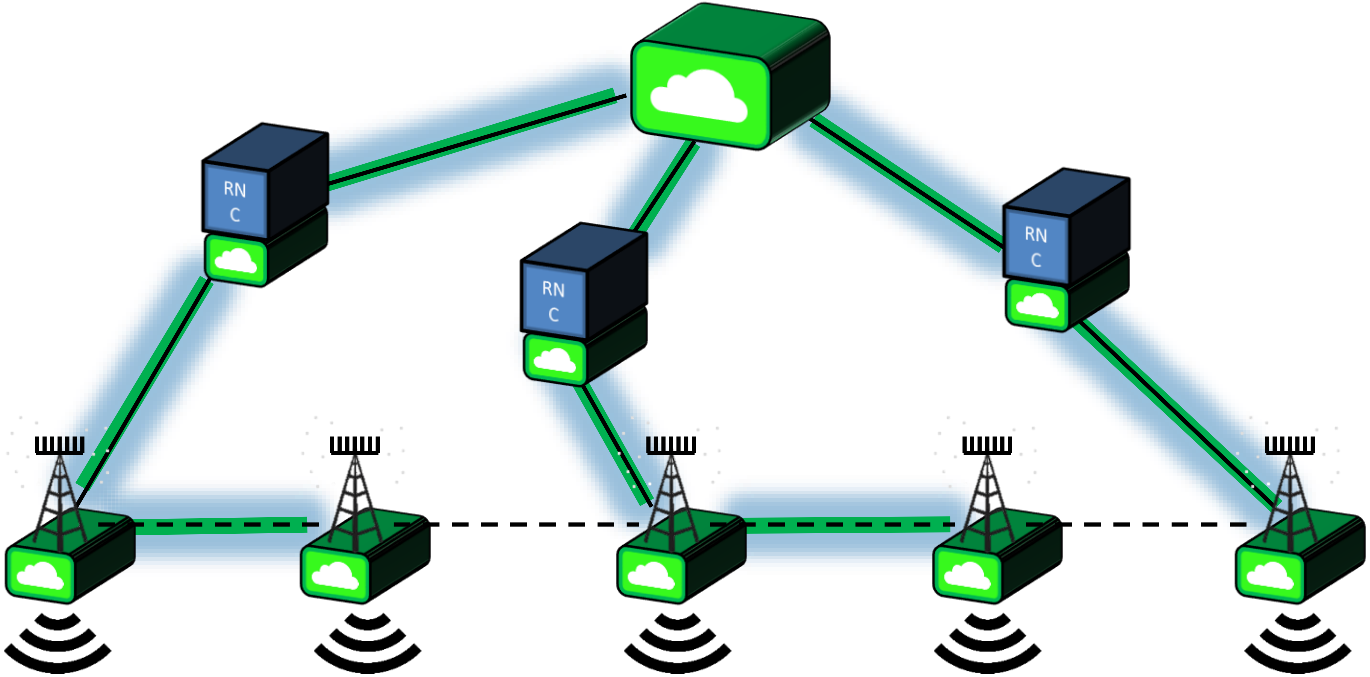


- Speed-Up (5 clouds)
- RLNC does not need full degree of freedom



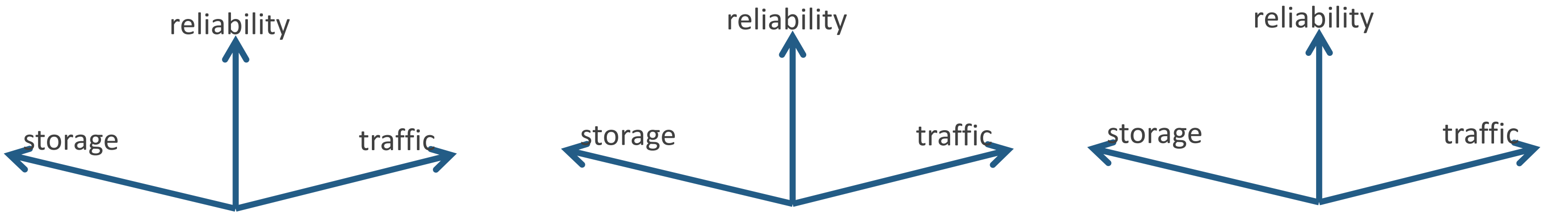
- M. Sipos, F.H.P. Fitzek, D. Lucani, and M.V. Pedersen, "Dynamic Allocation and Efficient Distribution of Data Among Multiple Clouds Using Network Coding," in IEEE International Conference on Cloud Networking (IEEE CloudNet'14), Oct. 2014.
- M. Sipos, F.H.P. Fitzek, D. Lucani, and M.V. Pedersen, "Distributed Cloud Storage Using Network Coding," in IEEE Consumer Communication and Networking Conference, Jan. 2014.

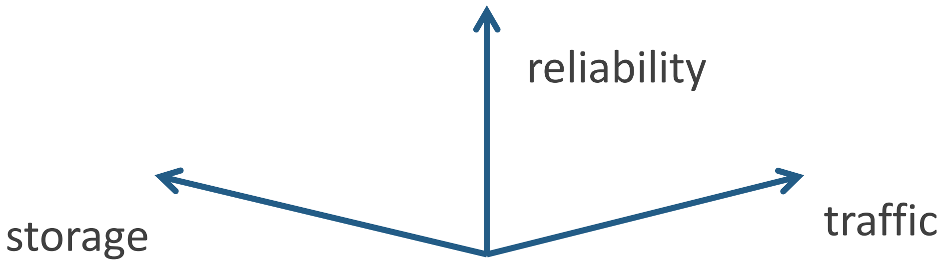
Mobile Edge Cloud / Micro Cloud / Cloud



Dynamic Distributed Cloud

No Coding | RS Coding | Network Coding



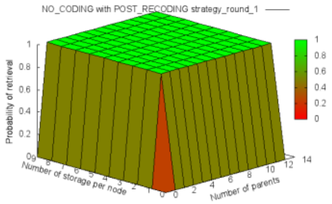


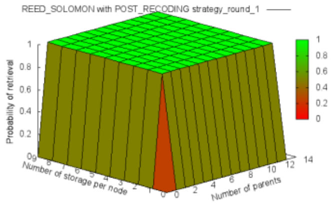
- F. Fitzek, T. Toth, A. Szabados, M.V. Pedersen, D. Lucani, M. Sipos, H. Charaf, and M. Medard, “Implementation and Performance Evaluation of Distributed Cloud Storage Solutions using Random Linear Network Coding,” in IEEE International Conference on Communications - Cooperative and Cognitve Network Workshop - CoCoNet6, June 2014.

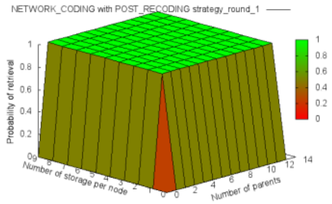
Data Survival over Time

No Coding | RS Coding | Network Coding

Distributed Policy

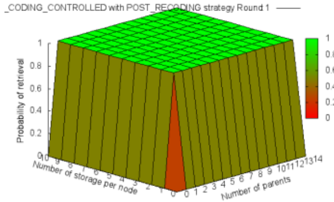


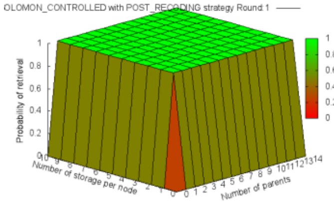


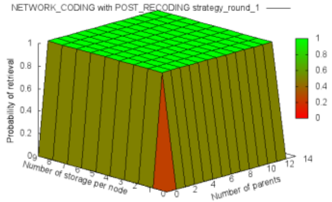


state-less

„Genie" Policy

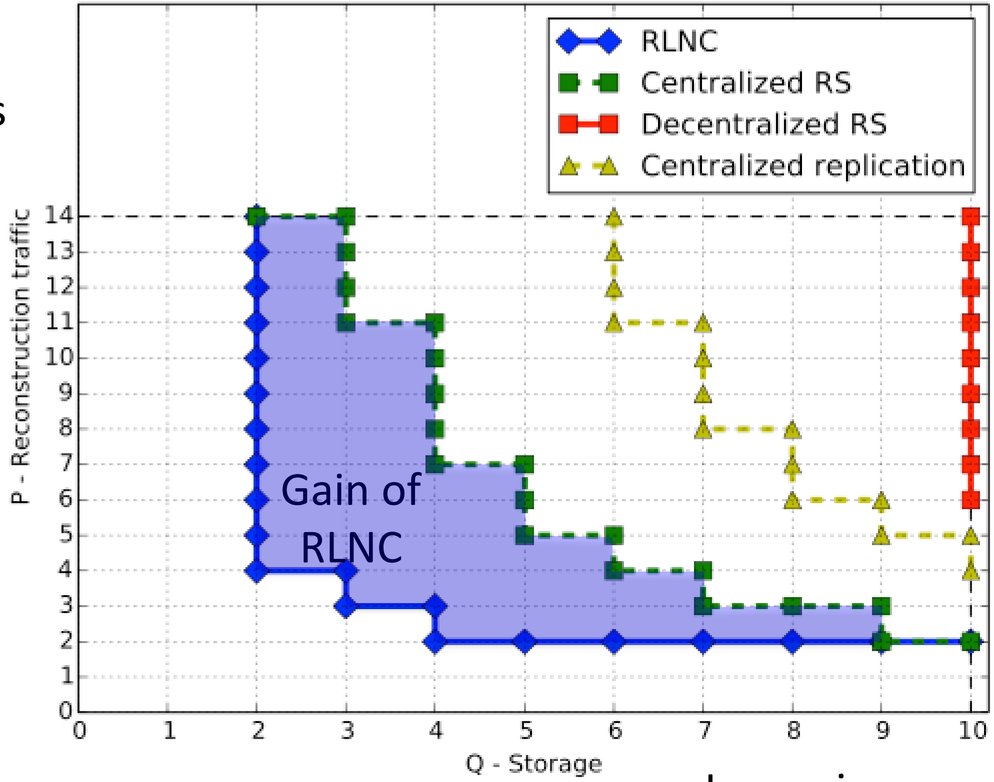






Data Survival (large # of runs)

Lower is better



Top view of 3D plots

Lower is better

5G COMPUTING

5G LAB GERMANY

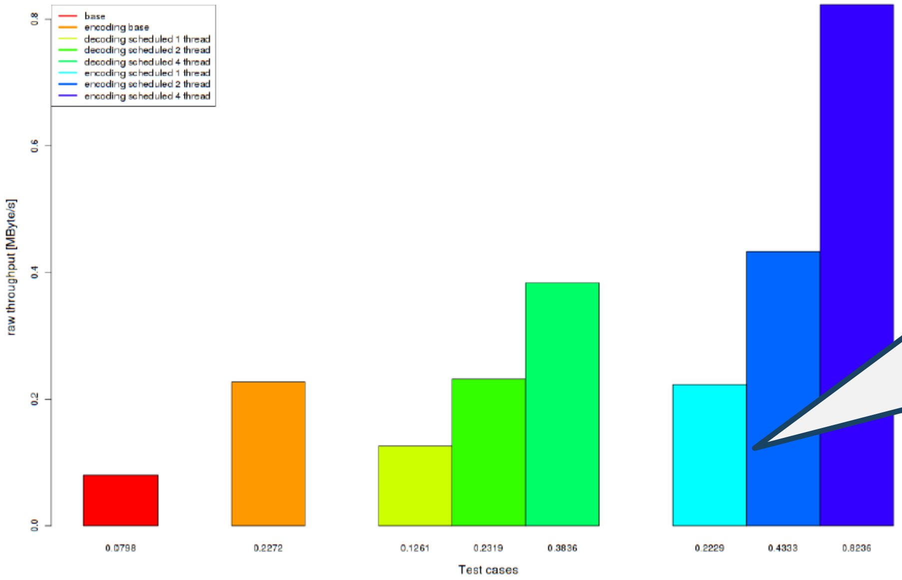
KODO Coding Speeds

Industry trend

F=GF(2^8) P=1MB	Kodo 17 MT (sparse=0.5)	Kodo 17 (sparse=0.5)	ISA-L	Jerasure 2.0	OpenFEC
G=8 (12)	3096/2980	3096/2980	2255/2635	1250/1365	353/292
G=9 (13)	2542/2559	2752/2898	1961/2252	1096/1185	305/264
G=10 (15)	2136/2227	2025/2126	1724/1796	997/1072	285/245
G=16 (24)	1807/1496	1264/1239	1075/1180	628/644	179/160
G=30 (45)	950/647	672/513	266/271	349/361	96/90
G=60 (90)	594/329	359/256	123/122	184/184	48/46
G=100 (150)	383/209	226/159	74/73	111/111	29/28
G=150 (225)	266/141	153/107	47/46	74/74	19/19

Measured on Intel(R) Core(TM) i7-4770 CPU @ 3.40GHz

Many-Core Implementation of Network Coding

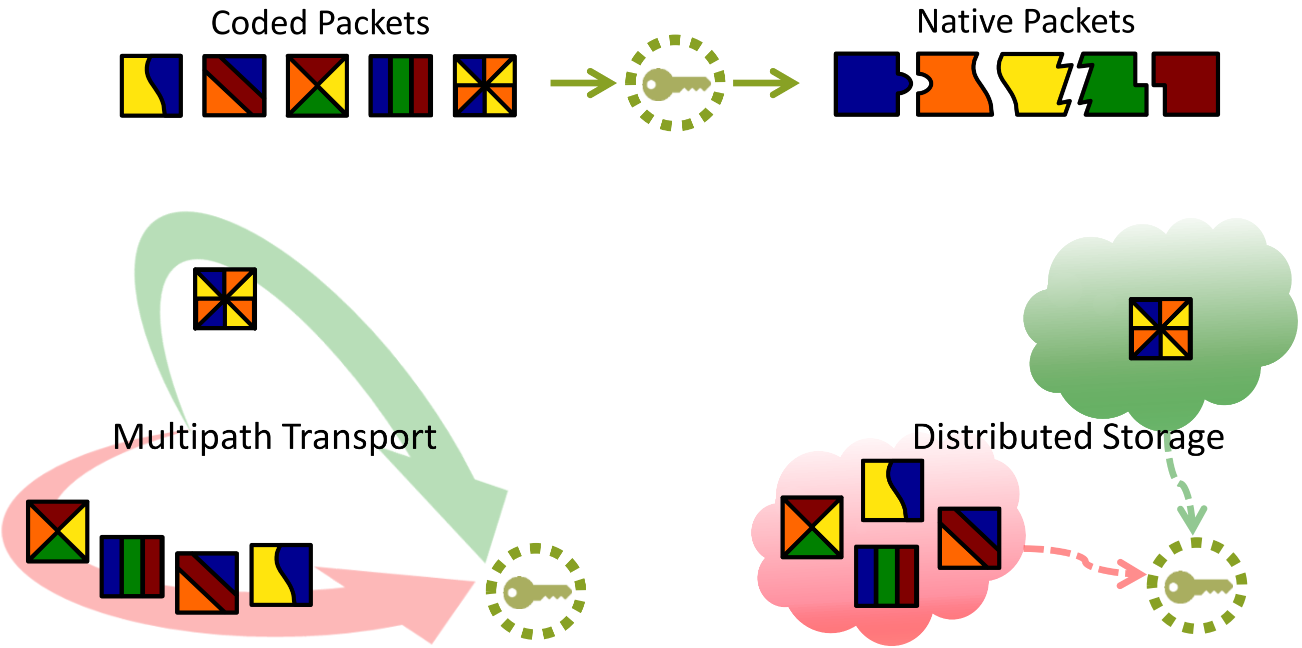


Herb Sutter: „Free lunch is over!“

Lots of research in computer science and engineering focus on achieving low computational complexity (the big O). But perhaps in the future we need to consider algorithms with worse computational complexity but which are easy to parallelize.

On Raspberry Pi 2: 10x speed up over standard SIMD encoding by using 4 cores and cache optimization (generation size 1024)

Coding as an Additional Security Measure



Data on a given path/cloud acts as a cypher

ONE CODE
TO RULE THEM ALL!

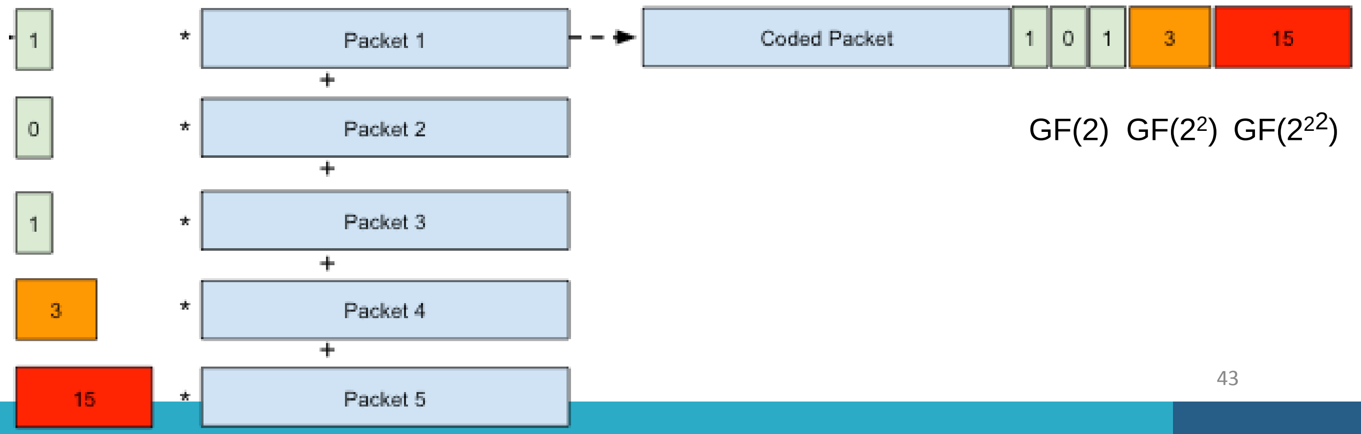
Telescopic Codes

Design:

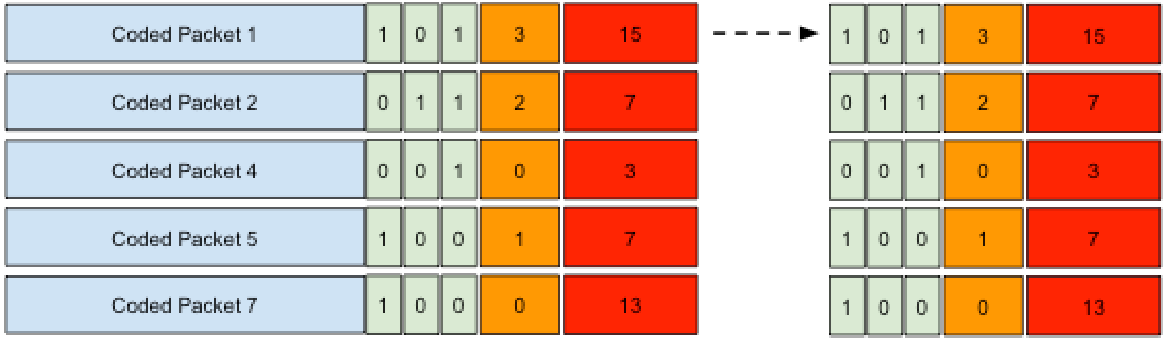
Multiple composite extension fields

Goal: reduce overhead, maintaining high performance, faster encoding/decoding

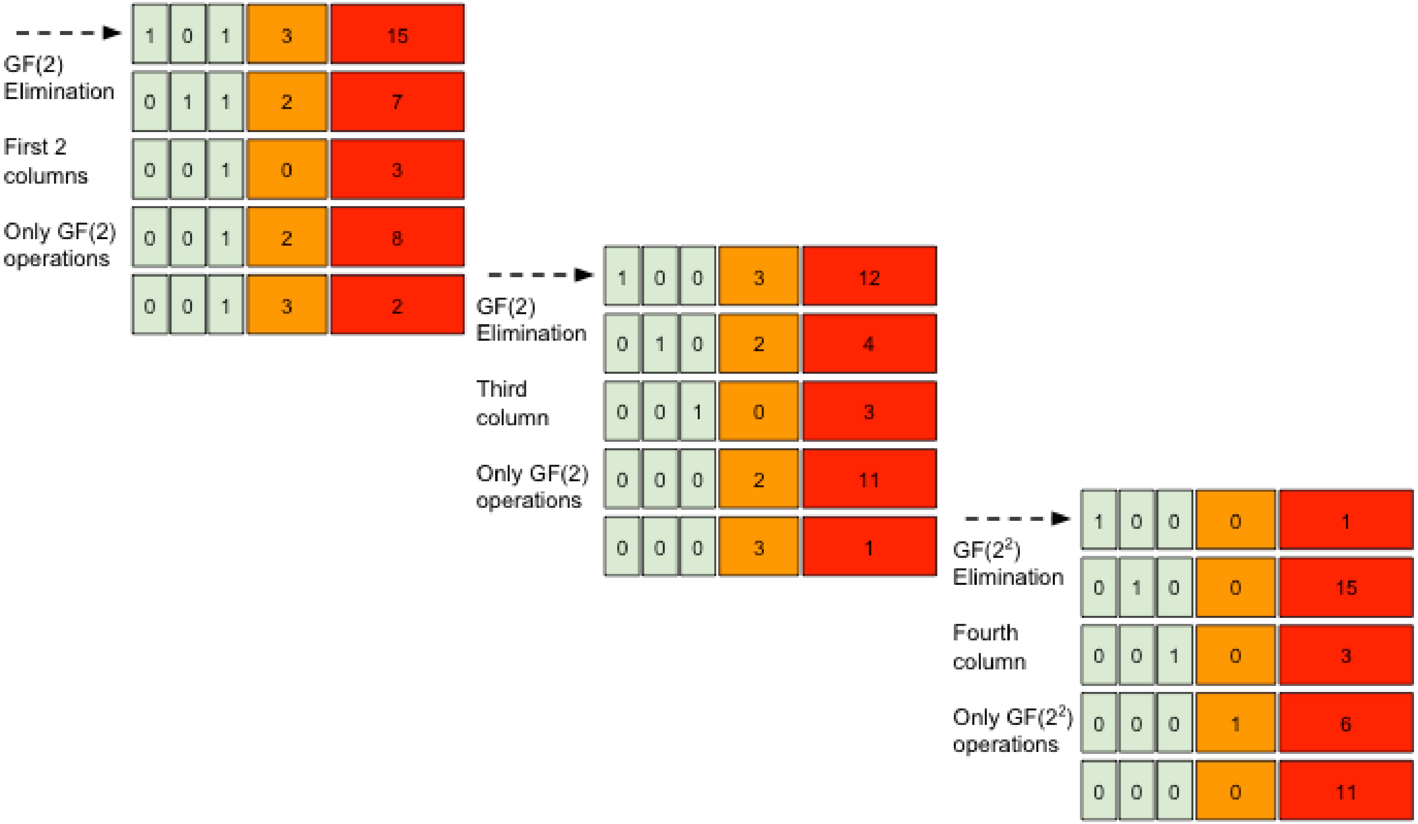
Different packets are encoded using different field sizes



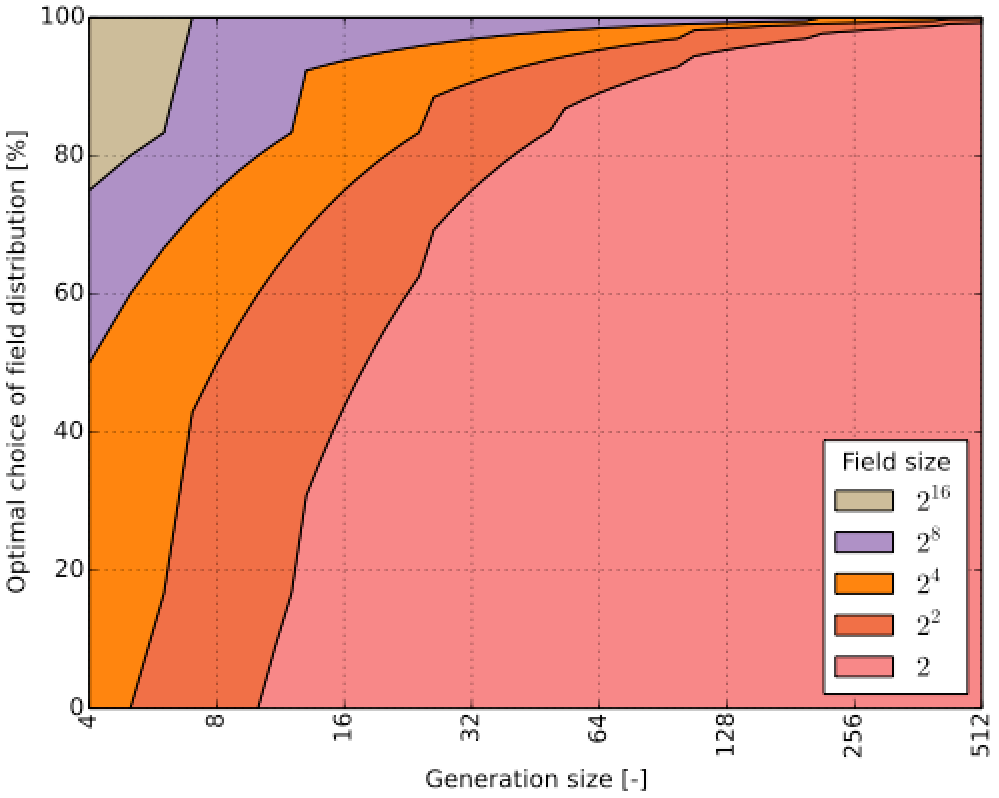
Telescopic Codes: Decoder



Telescopic Codes: Decoder



Results



Optimal choice of field distribution [%]
100
80
60
40
20
0
4
8
16
32
64
128
256
512
Generation size [-]
Field size
2^{16}
2^{8}
2^{4}
2^{2}
2

General Ideas

Fluid allocation of complexity

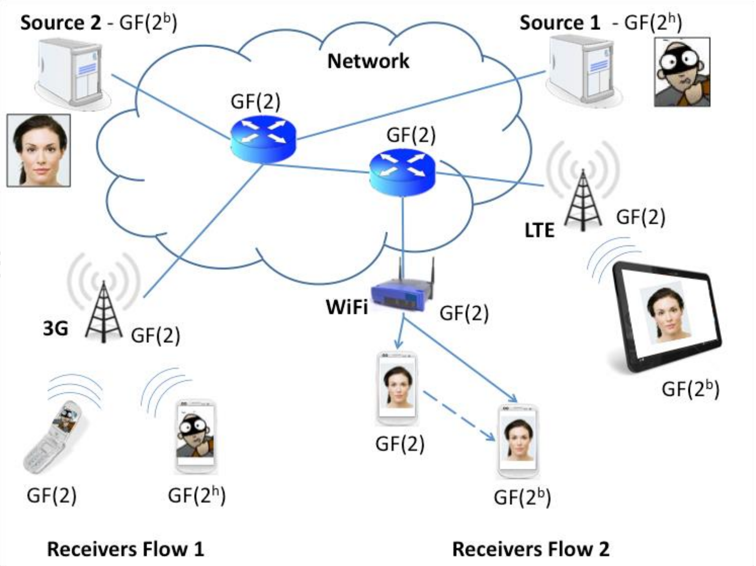
End devices agree on desired performance:

- Independent from network
- Chosen according to application requirements

Network devices need only support a simple

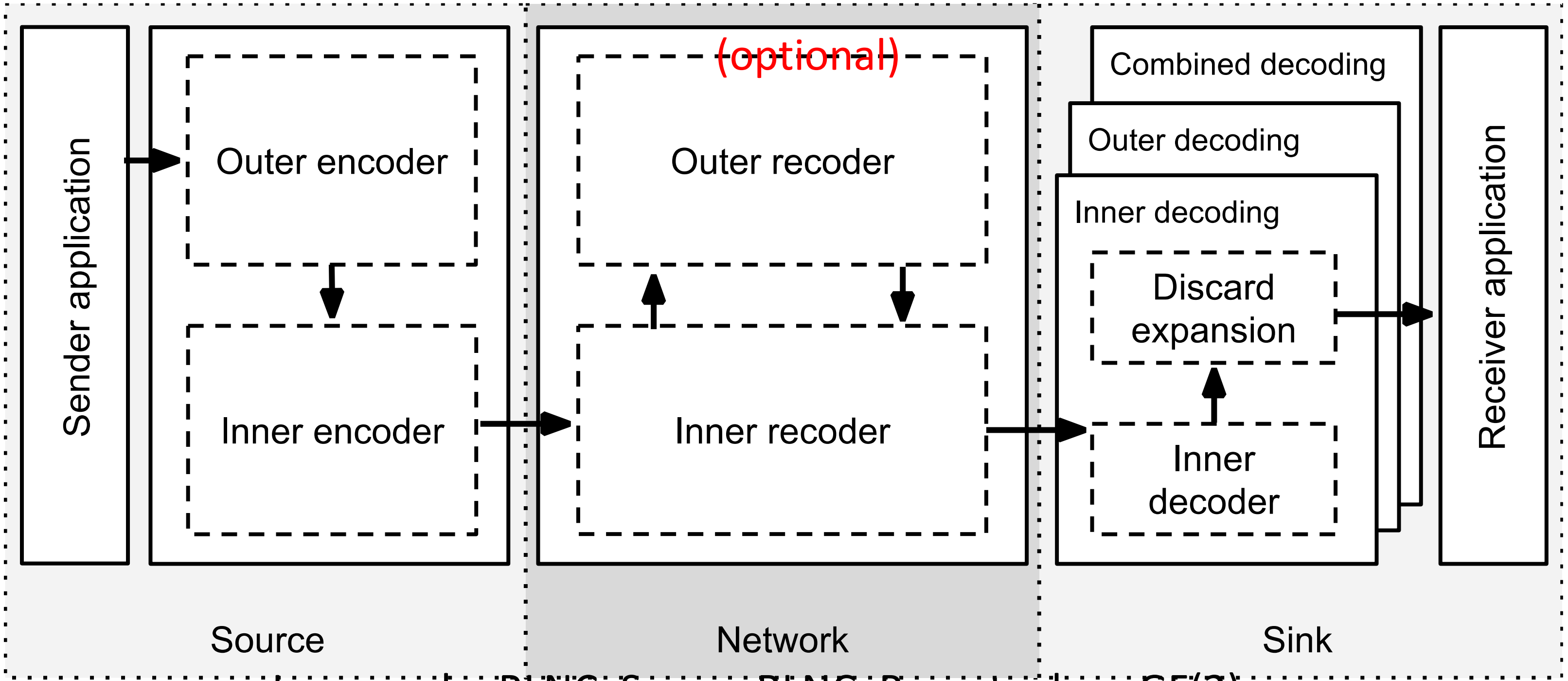
Reduces overhead

- Roughly 1 bit per coding coefficient



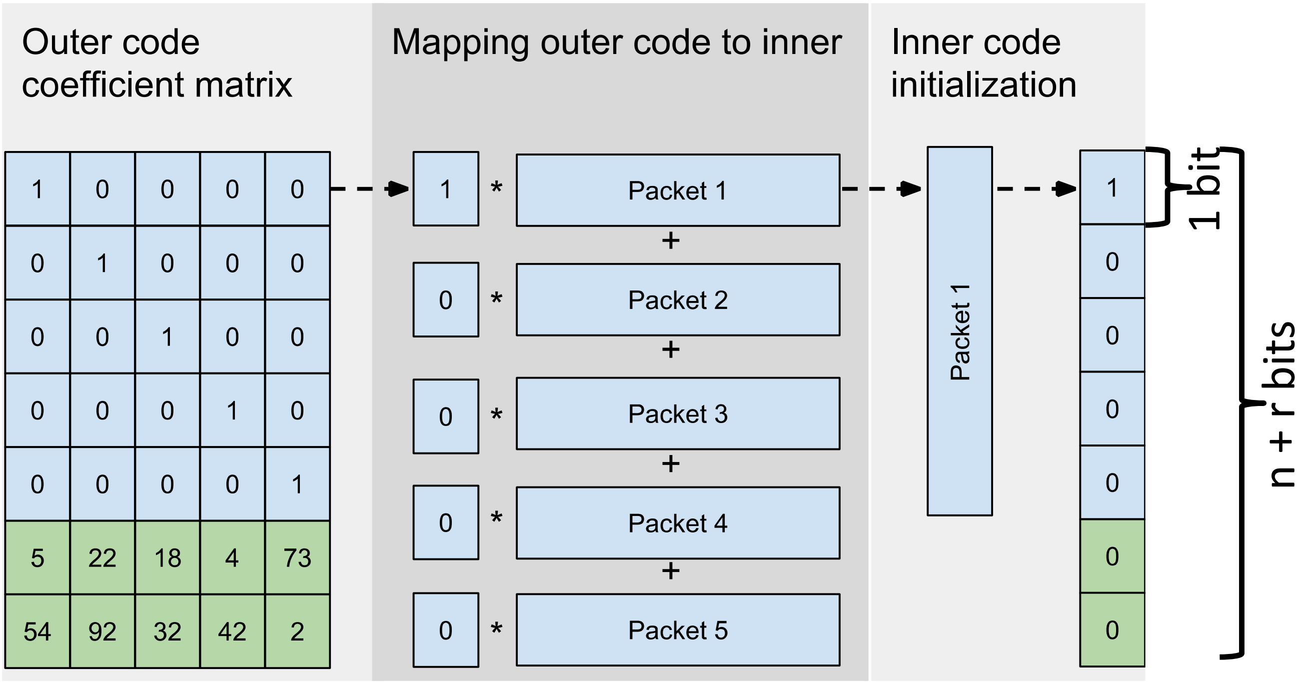
Key: code concatenation with different field sizes

General Structure



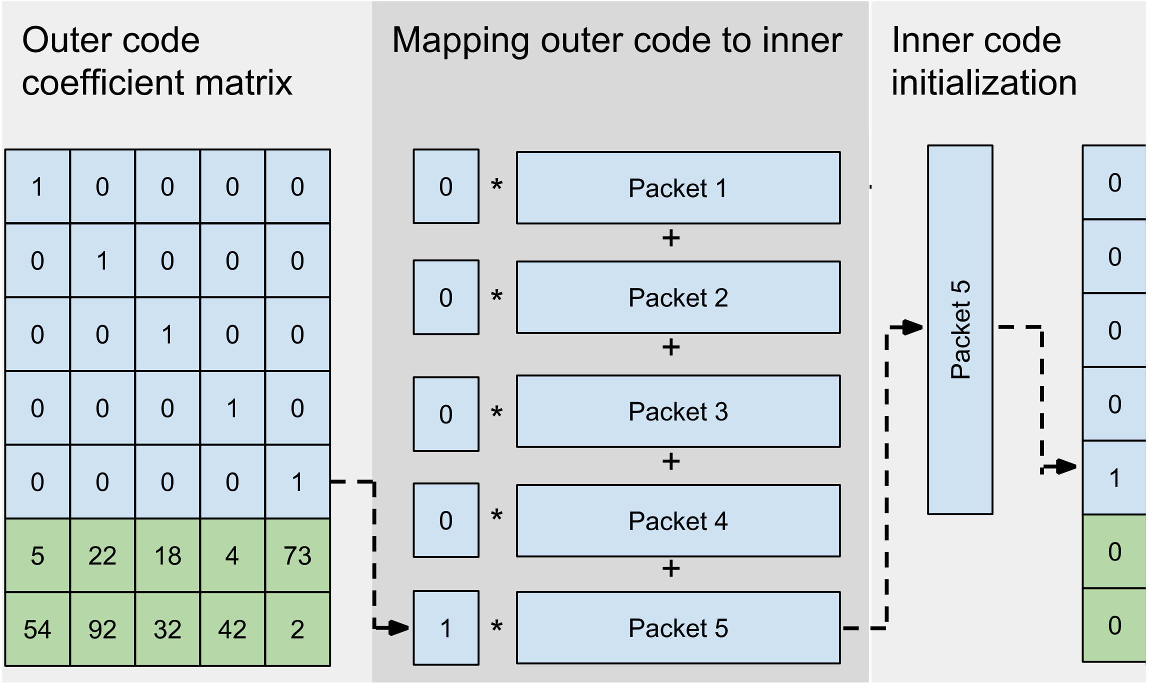
- Inner code: RLNC, Sparse RLNC, Perpetual, … GF(2)
- Outer code: (systematic) RLNC, Reed-Solomon, … GF(2^h)

Encoder



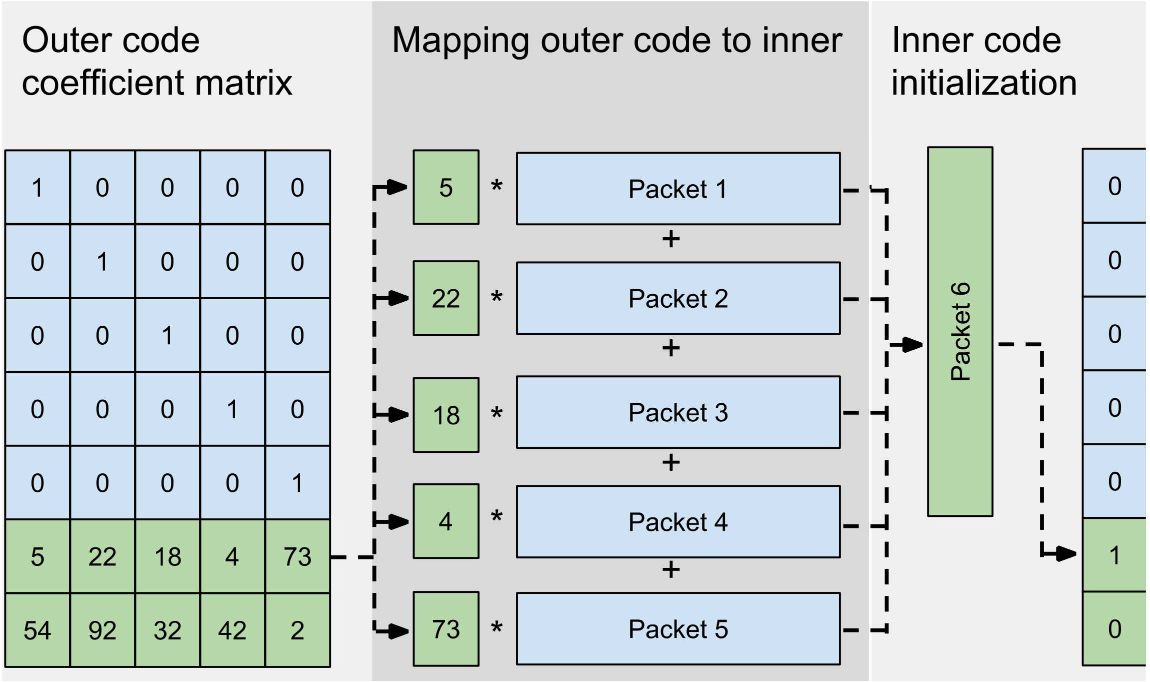
Outer code coefficient matrix
1
0
0
0
0
0
1
0
0
0
0
0
1
0
0
0
0
0
1
0
0
0
0
0
1
5
22
18
4
73
54
92
32
42
2
Mapping outer code to inner
1 * Packet 1
+
0 * Packet 2
+
0 * Packet 3
+
0 * Packet 4
+
0 * Packet 5
Inner code initialization
Packet 1
1
0
0
0
0
0
0
1 bit
n + r bits

Encoder



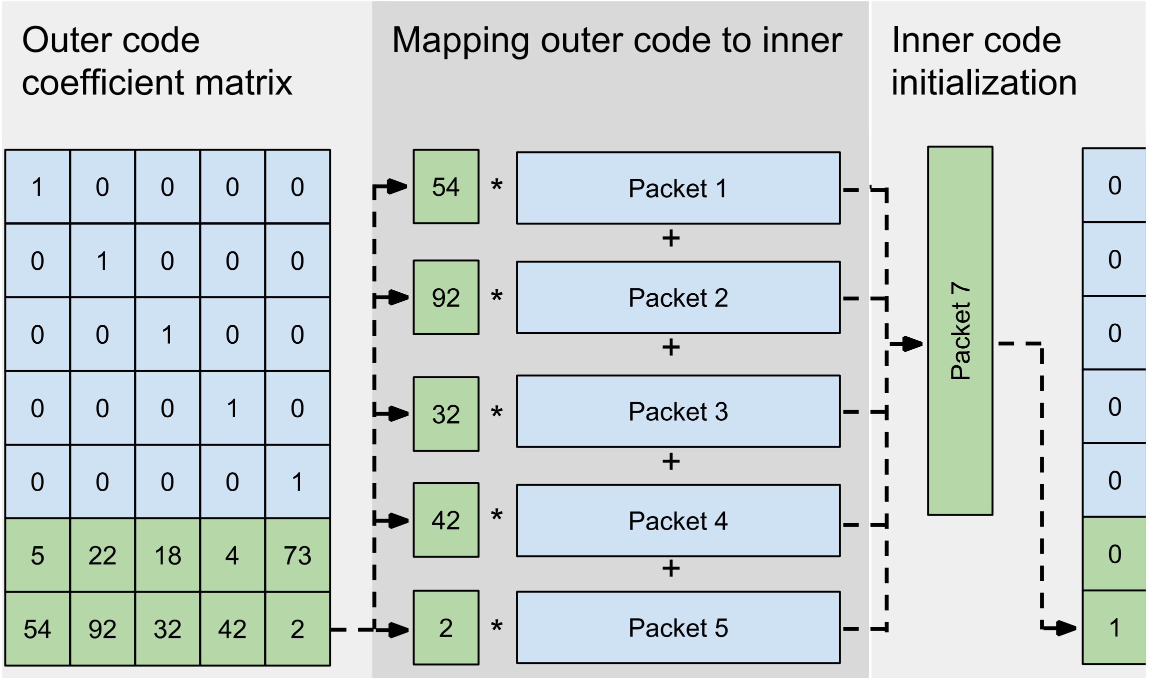
Outer code coefficient matrix
1 0 0 0 0
0 1 0 0 0
0 0 1 0 0
0 0 0 1 0
0 0 0 0 1
5 22 18 4 73
54 92 32 42 2
Mapping outer code to inner
0 * Packet 1
+
0 * Packet 2
+
0 * Packet 3
+
0 * Packet 4
+
1 * Packet 5
Inner code initialization
Packet 5
0
0
0
0
1
0
0

Encoder



Outer code
coefficient matrix
Mapping outer code to inner
Inner code
initialization
1 0 0 0 0
0 1 0 0 0
0 0 1 0 0
0 0 0 1 0
0 0 0 0 1
5 22 18 4 73
54 92 32 42 2
5 * Packet 1
+
22 * Packet 2
+
18 * Packet 3
+
4 * Packet 4
+
73 * Packet 5
Packet 6
0
0
0
0
0
1
0

Encoder



Outer code coefficient matrix
Mapping outer code to inner
Inner code initialization
1 0 0 0 0
0 1 0 0 0
0 0 1 0 0
0 0 0 1 0
0 0 0 0 1
5 22 18 4 73
54 92 32 42 2
54 * Packet 1
+
92 * Packet 2
+
32 * Packet 3
+
42 * Packet 4
+
2 * Packet 5
Packet 7
0
0
0
0
0
0
1

Received Packets before Decoding

5G LAB GERMANY

Code		Decoding after receiving (coded packets)			
		n	n + 1	n + 2	n + 3
Fulcrum	r = 4	93.87%	99.75%	99.99%	99.9997%
	r = 7	99.22%	99.996%	99.99998%	99.99999992%
	r = 10	99.90%	99.9999%	99.99999996%	99.99999999998 %
RaptorQ*		99%	99.99%	99.9999%	

* Qualcomm. (2013, Dec.) Raptorq - the superior fec technology Available: http://www.qualcomm.com/media/documents/raptorq-data