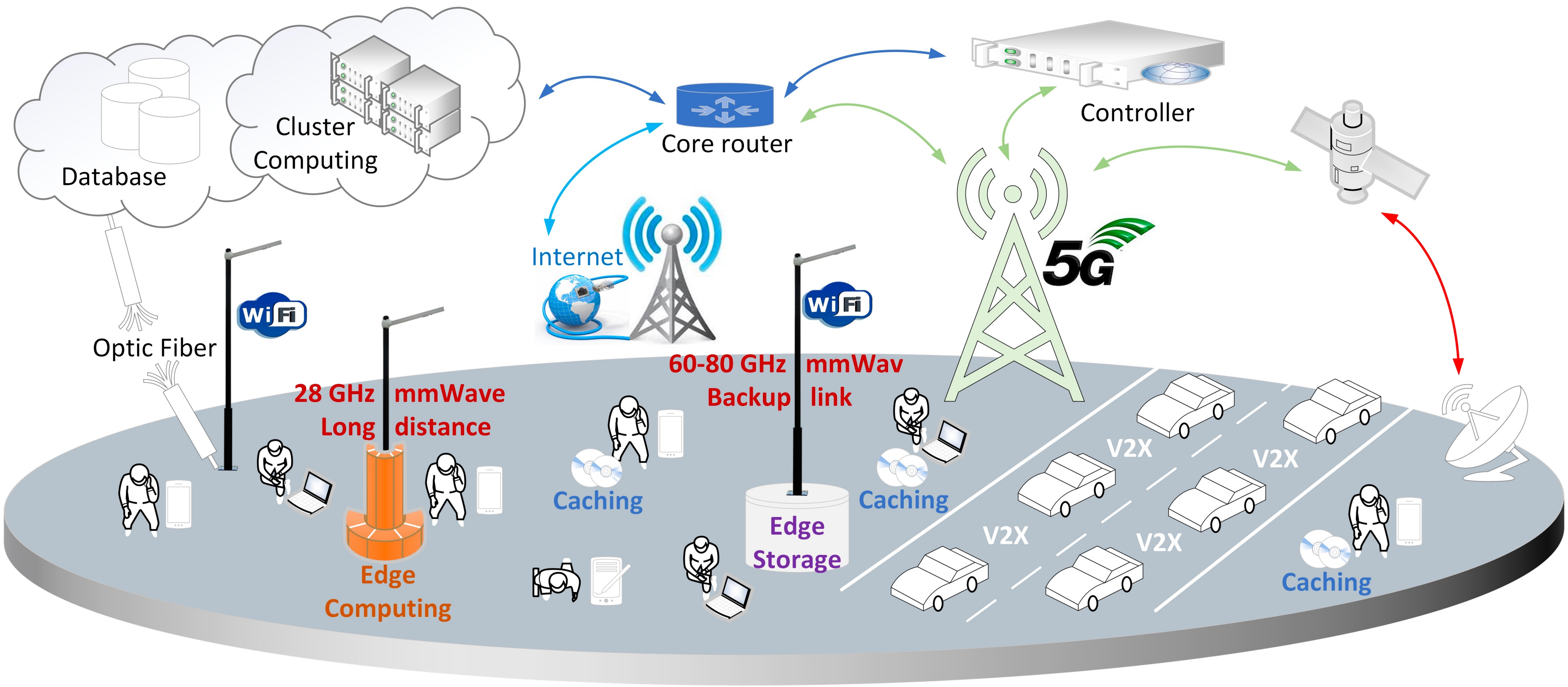
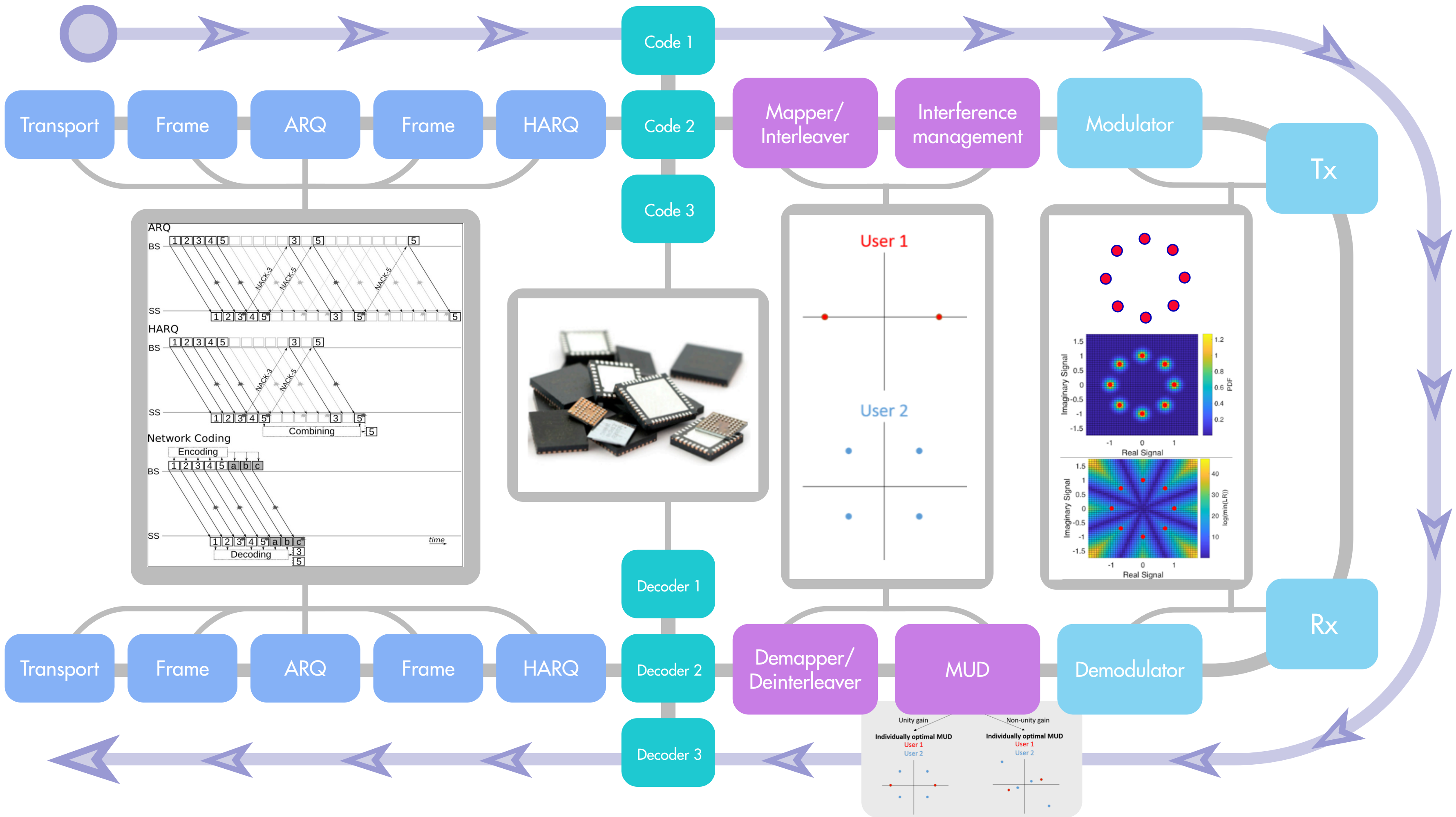
6G – can we escape gravity?

Muriel Médard

ELLITT 6G Symposium
November 2023

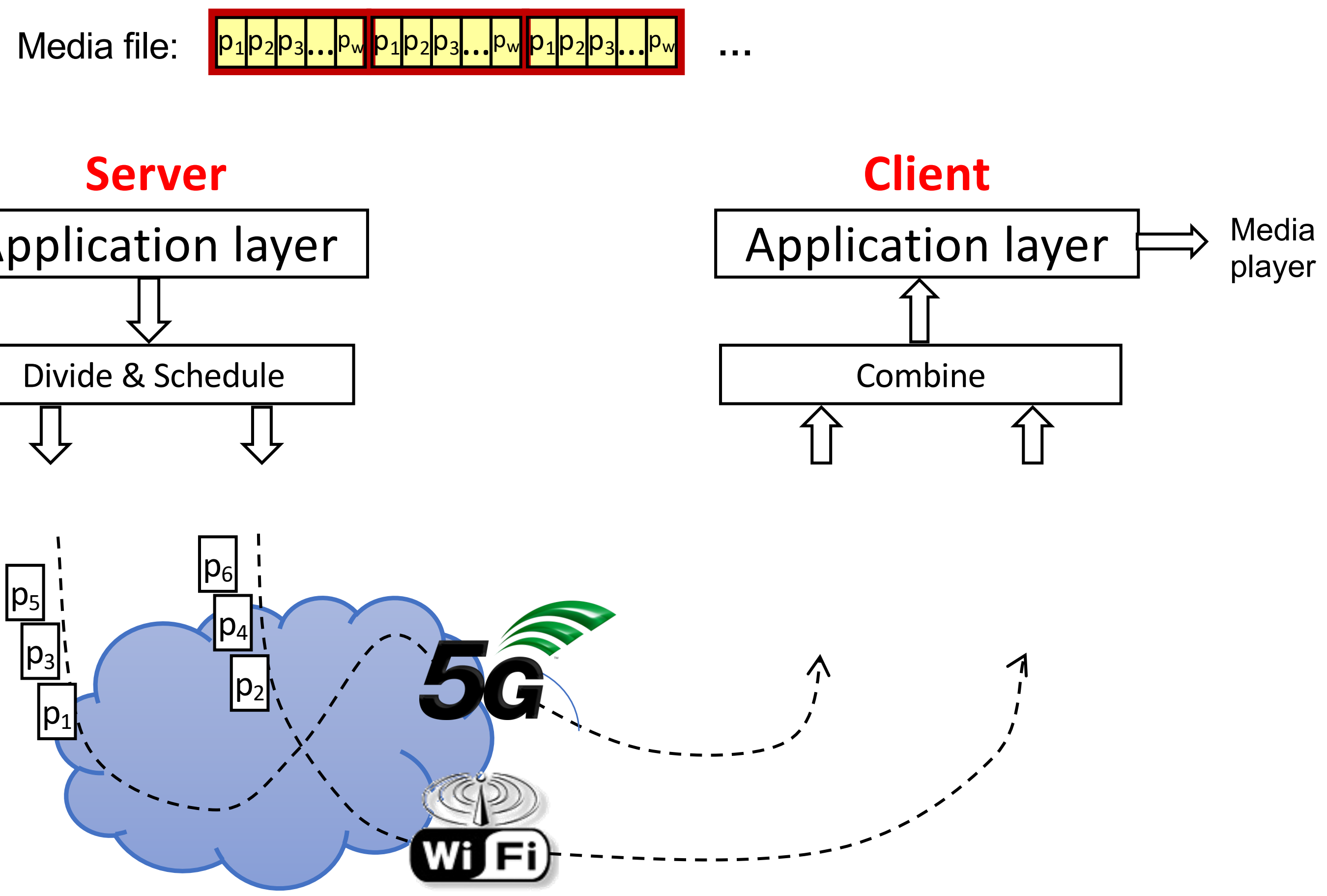
A Complex System



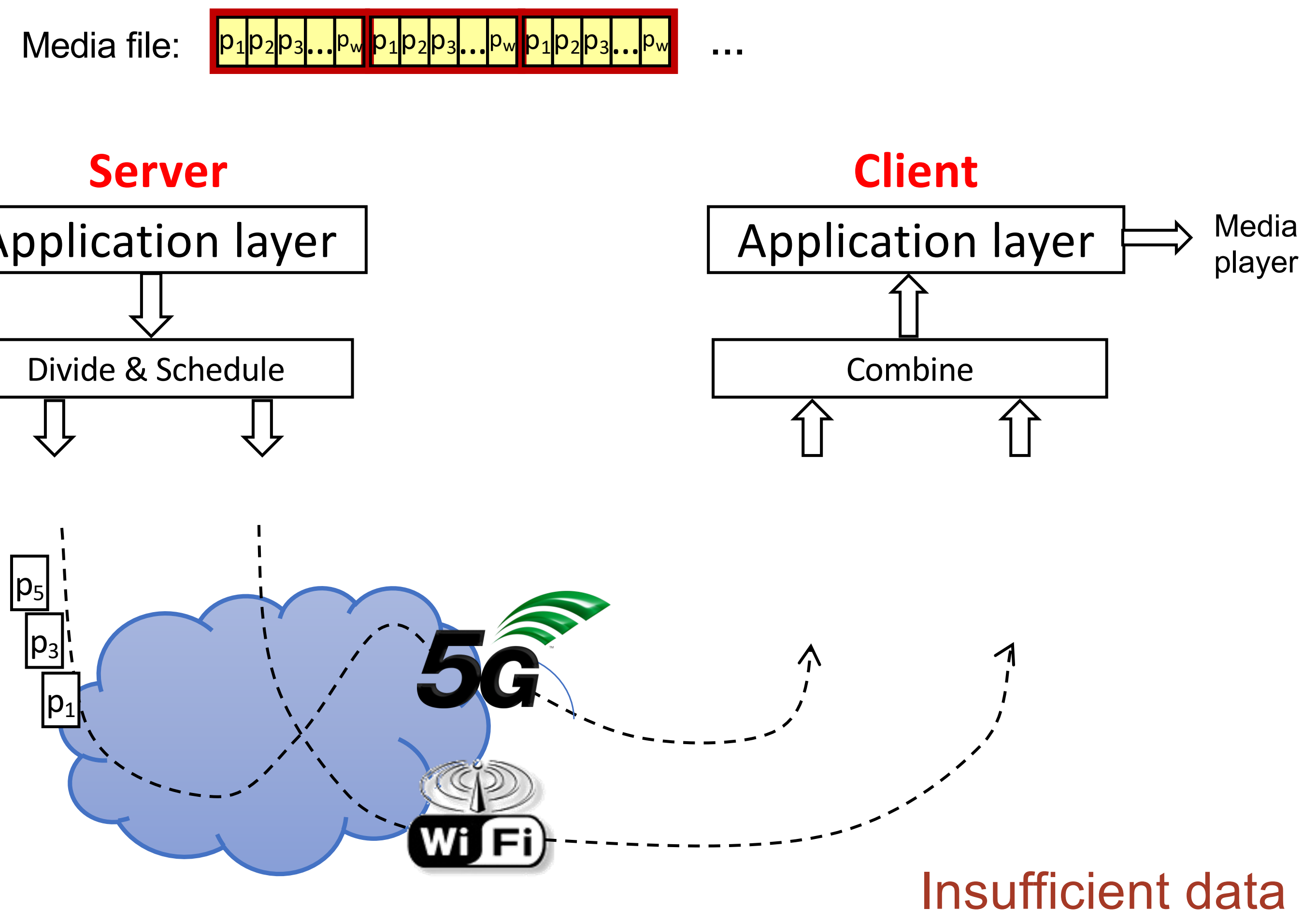


Code 1
Code 2
Code 3
Transport
Frame
ARQ
Frame
HARQ
Mapper/ Interleaver
Interference management
Modulator
Tx
ARQ
HARQ
Network Coding
Encoding
Combining
Decoding
time
User 1
User 2
Real Signal
Imaginary Signal
PDF
Rx
Decoder 1
Decoder 2
Decoder 3
Transport
Frame
ARQ
Frame
HARQ
Demapper/ Deinterleaver
MUD
Demodulator
Unity gain
Non-unity gain
Individually optimal MUD

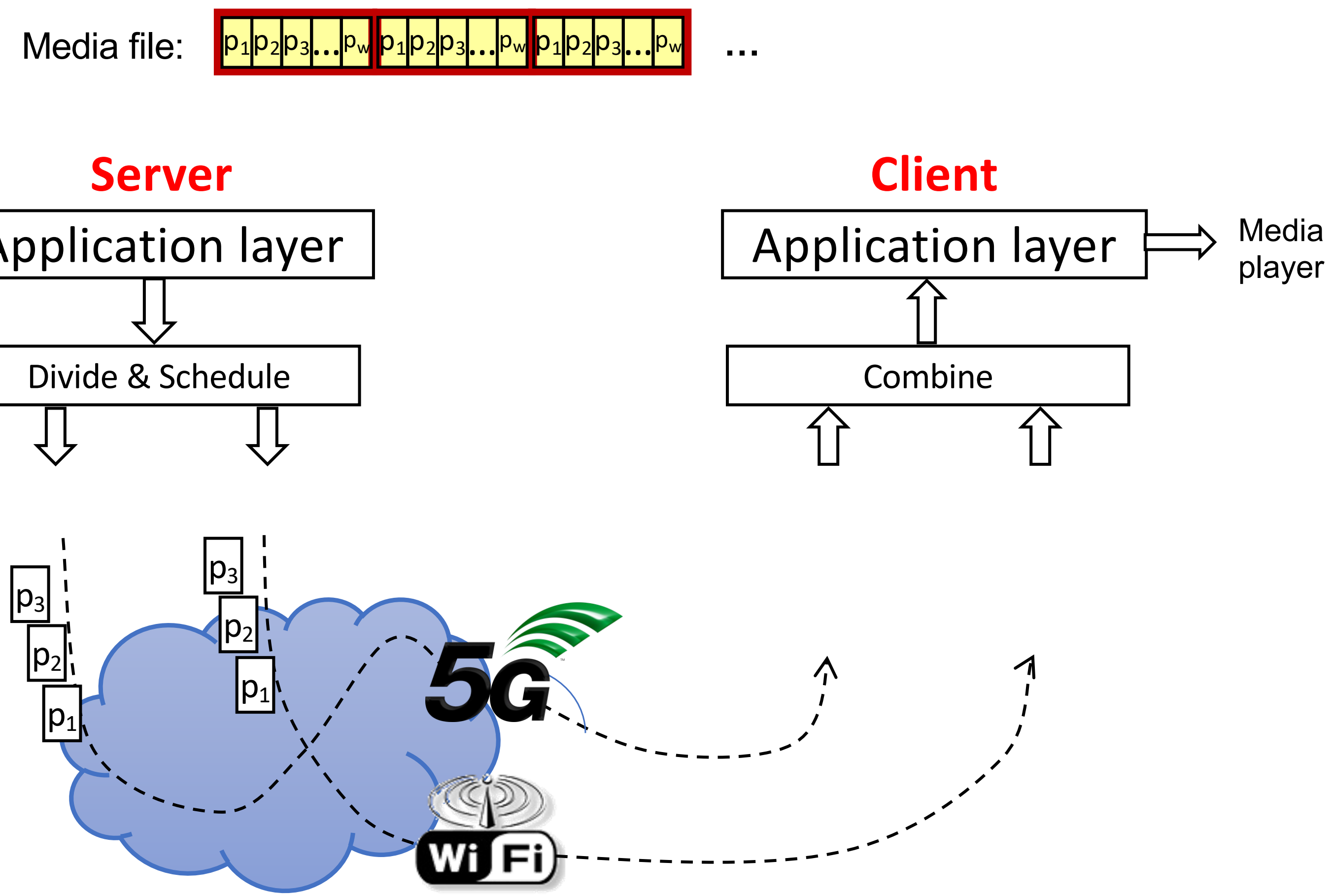
Heterogeneity in Networks



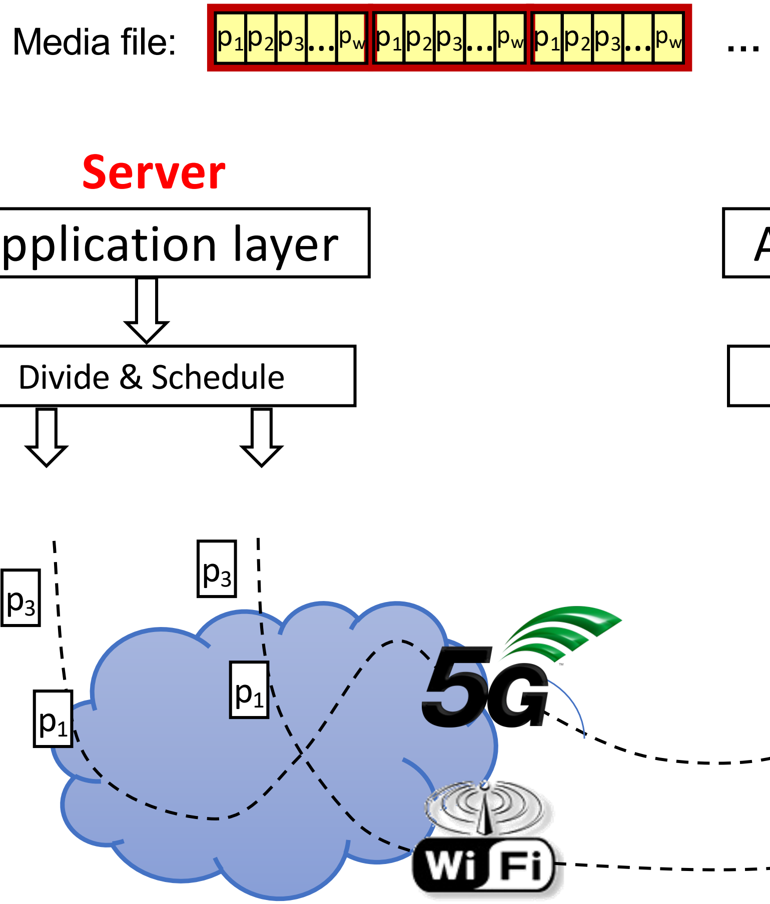
Heterogeneity in Networks



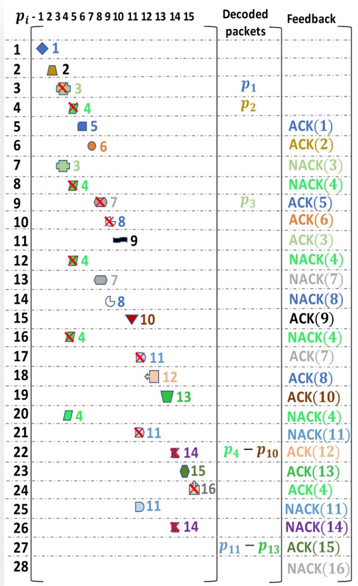
Heterogeneity in Networks



Heterogeneity in Networks

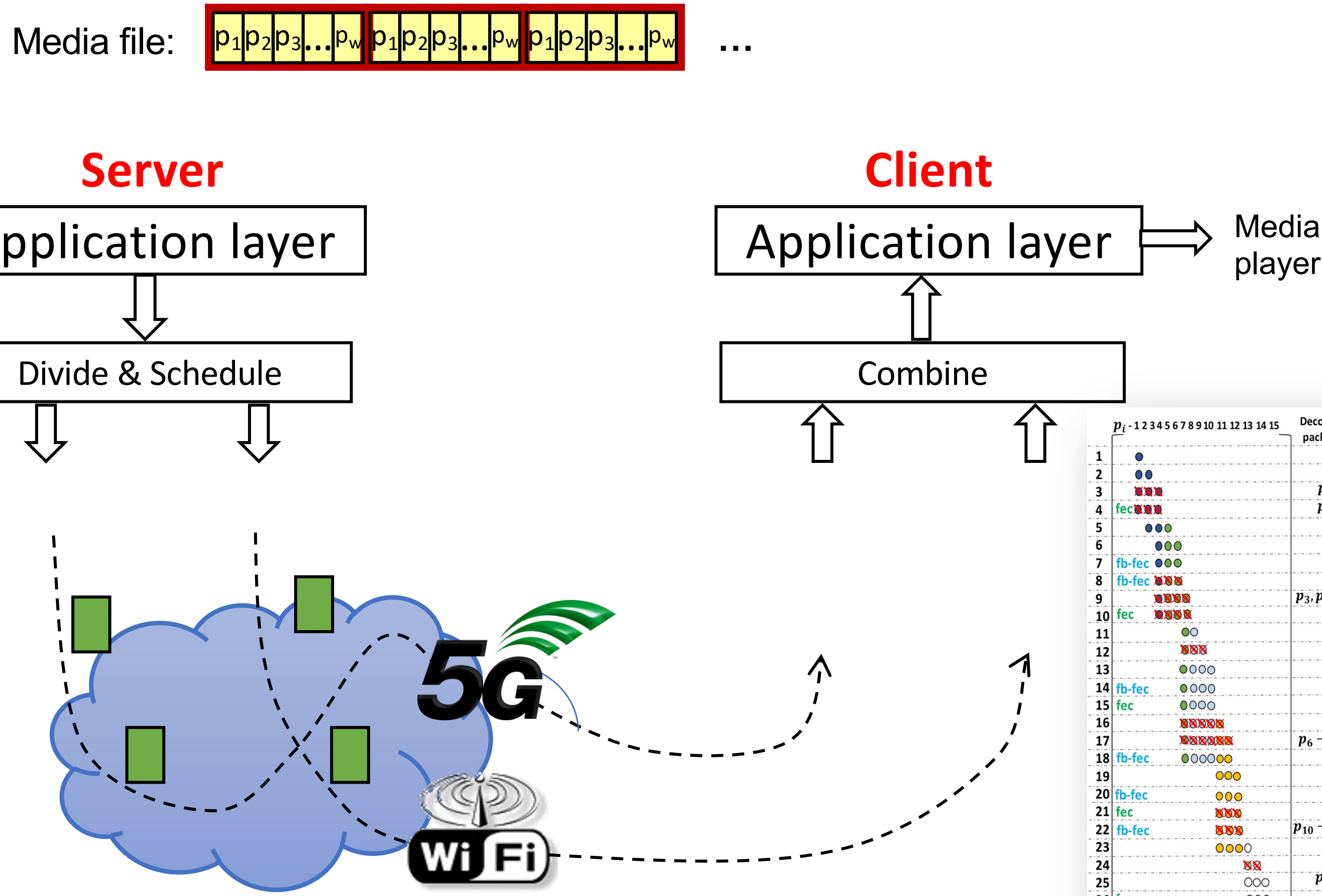


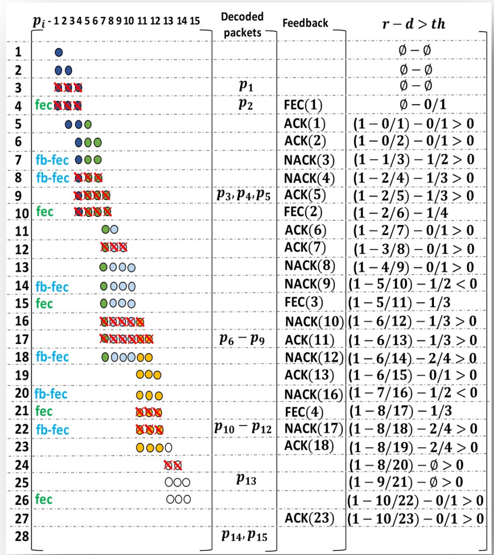
Repetition with ARQ



Heterogeneity in Networks

Coding

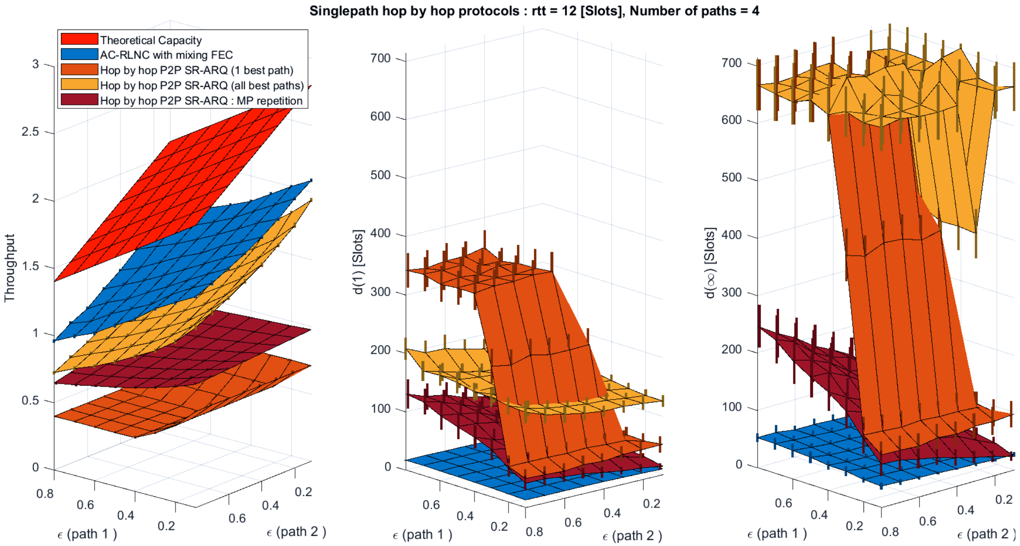




	p_i - 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15	Decoded packets	Feedback	$r - d > th$
1				$\emptyset - \emptyset$
2				$\emptyset - \emptyset$
3		p_1		$\emptyset - \emptyset$
4	fec	p_2	FEC(1)	$\emptyset - 0/1$
5			ACK(1)	$(1 - 0/1) - 0/1 > 0$
6			ACK(2)	$(1 - 0/2) - 0/1 > 0$
7	fb-fec		NACK(3)	$(1 - 1/3) - 1/2 > 0$
8	fb-fec		NACK(4)	$(1 - 2/4) - 1/3 > 0$
9		p_3, p_4, p_5	ACK(5)	$(1 - 2/5) - 1/3 > 0$
10	fec		FEC(2)	$(1 - 2/6) - 1/4$
11			ACK(6)	$(1 - 2/7) - 0/1 > 0$
12			ACK(7)	$(1 - 3/8) - 0/1 > 0$
13			NACK(8)	$(1 - 4/9) - 0/1 > 0$
14	fb-fec		NACK(9)	$(1 - 5/10) - 1/2 < 0$
15	fec		FEC(3)	$(1 - 5/11) - 1/3$
16			NACK(10)	$(1 - 6/12) - 1/3 > 0$
17		$p_6 - p_9$	ACK(11)	$(1 - 6/13) - 1/3 > 0$
18	fb-fec		NACK(12)	$(1 - 6/14) - 2/4 > 0$
19			ACK(13)	$(1 - 6/15) - 0/1 > 0$
20	fb-fec		NACK(16)	$(1 - 7/16) - 1/2 < 0$
21	fec		FEC(4)	$(1 - 8/17) - 1/3$
22	fb-fec	$p_{10} - p_{12}$	NACK(17)	$(1 - 8/18) - 2/4 > 0$
23			ACK(18)	$(1 - 8/19) - 2/4 > 0$
24				$(1 - 8/20) - \emptyset > 0$
25		p_{13}		$(1 - 9/21) - \emptyset > 0$
26	fec			$(1 - 10/22) - 0/1 > 0$
27			ACK(23)	$(1 - 10/23) - 0/1 > 0$
28		p_{14}, p_{15}		

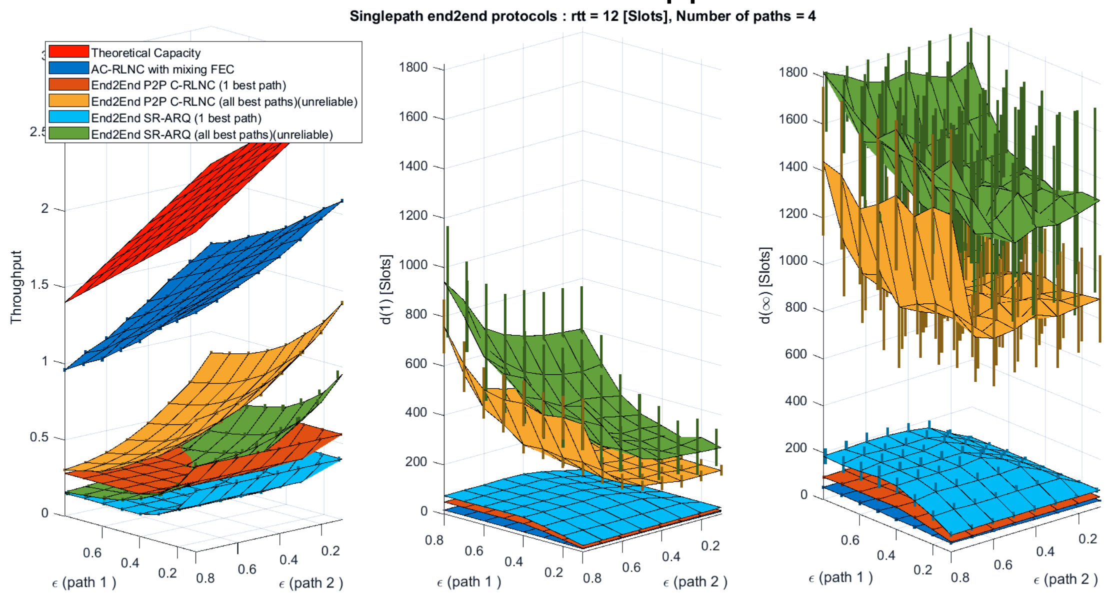
Mesh networks

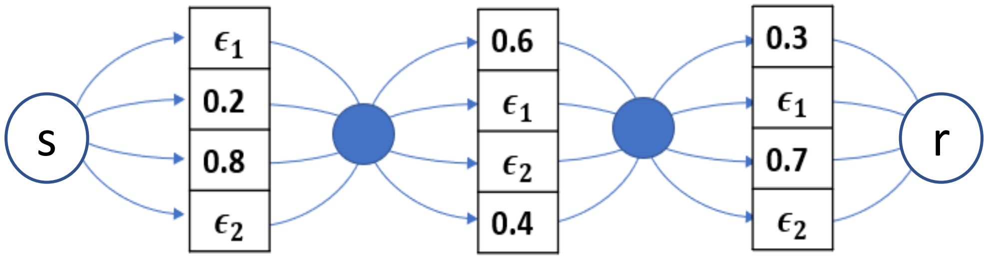
A. Cohen, D. Malak, V. B. Bracha and M. Médard, *IEEE Transactions on Communications*, 2020



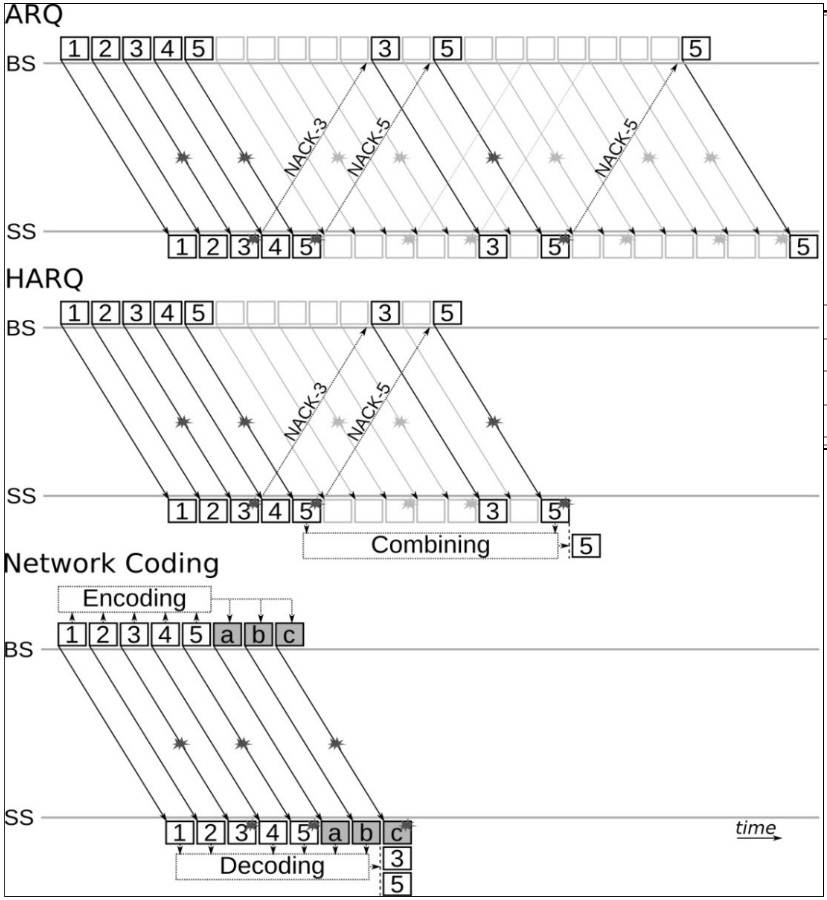
Coded adaptive feedback can outperform hop by hop or end-to-end coded approaches

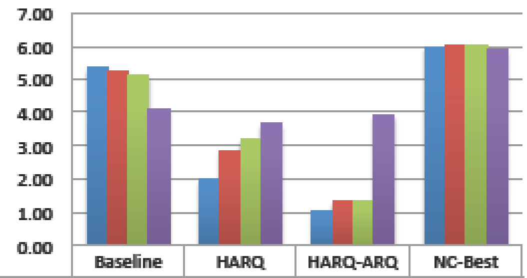
- Delay sensitivity *d(p)*
  - *p* = 1: only throughput matters
  - *p* = ∞: only in order delay matters
  - Other sensitivities for other applications





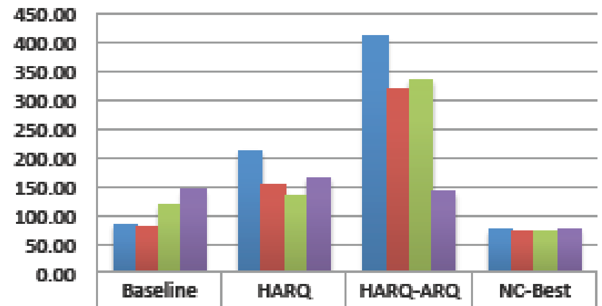
Using Feedback





	Baseline	HARQ	HARQ-ARQ	NC-Best
64 QAM 1/2 at 13 dB	5.33	1.97	1.02	5.98
64 QAM 2/3 at 17 dB	5.26	2.86	1.33	5.99
64 QAM 3/4 at 18 dB	5.13	3.18	1.32	5.99
64 QAM 5/6 at 20 dB	4.11	3.66	3.93	5.87

Throughput

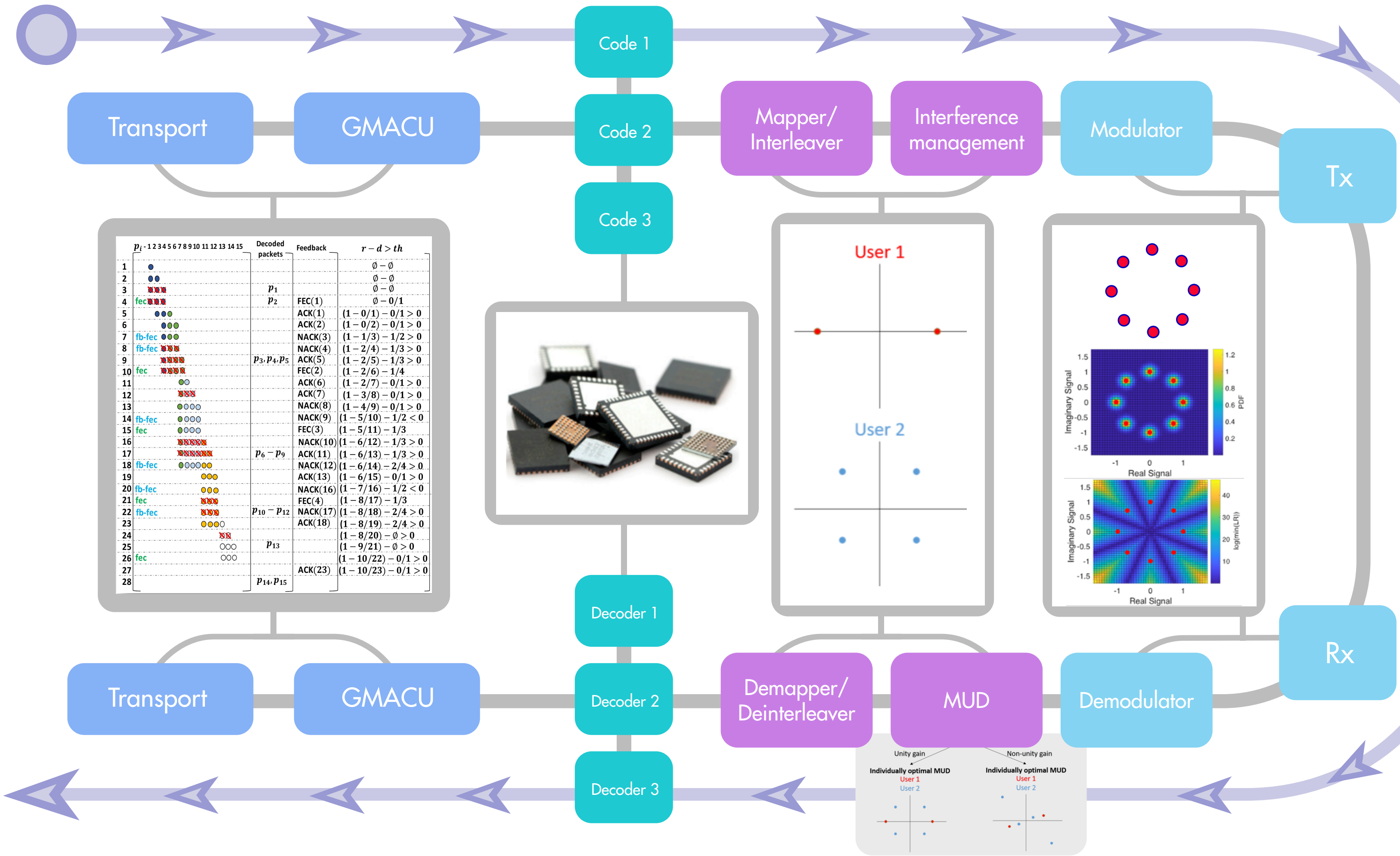


	Baseline	HARQ	HARQ-ARQ	NC-Best
64 QAM 1/2 at 13 dB	83.75	210.18	408.37	74.01
64 QAM 2/3 at 17 dB	78.88	150.03	315.82	70.03
64 QAM 3/4 at 18 dB	116.84	133.63	333.71	71.02
64 QAM 5/6 at 20 dB	141.99	164.68	139.34	76.06

File transfer delay

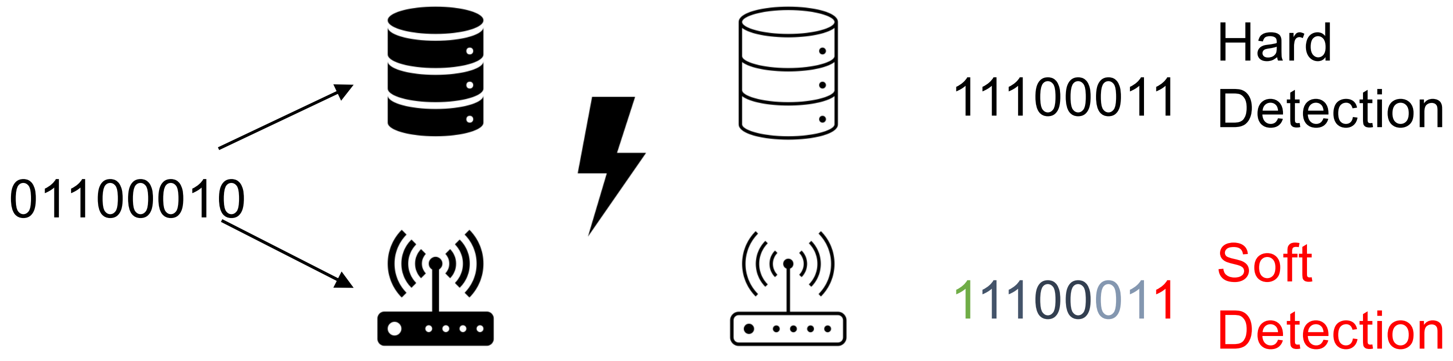
Turn off HARQ and traditional ARQ, turn on RLNC

S. Teerapittayanon, Fouli, K., Médard, M., Montpetit, M.-J., Shi, X., Seskar, I., and Gosain, A., *MACOM 2012.*


Code 1
Code 2
Code 3
Transport
GMACU
Mapper/
Interleaver
Interference
management
Modulator
Tx
User 1
User 2
Real Signal
Imaginary Signal
Decoder 1
Decoder 2
Decoder 3
Transport
GMACU
Demapper/
Deinterleaver
MUD
Demodulator
Rx
Unity gain
Non-unity gain
Individually optimal MUD
User 1
User 2
Individually optimal MUD
User 1
User 2

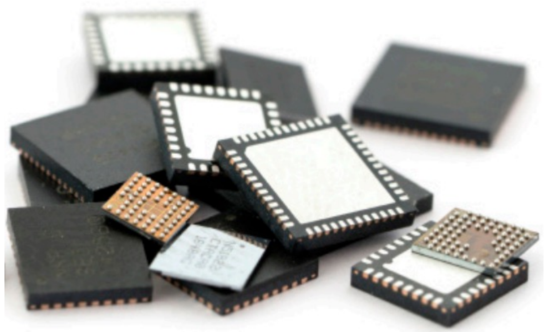
Error Correction

- To enable recovery of the original data, **all** systems use **error-correcting codes**
- Input of **k** bits is turned into **n** bits, resulting in **n-k redundant bits**
- The **rate** of the code is **R=k/n**, as there are k bits of information per each n bits

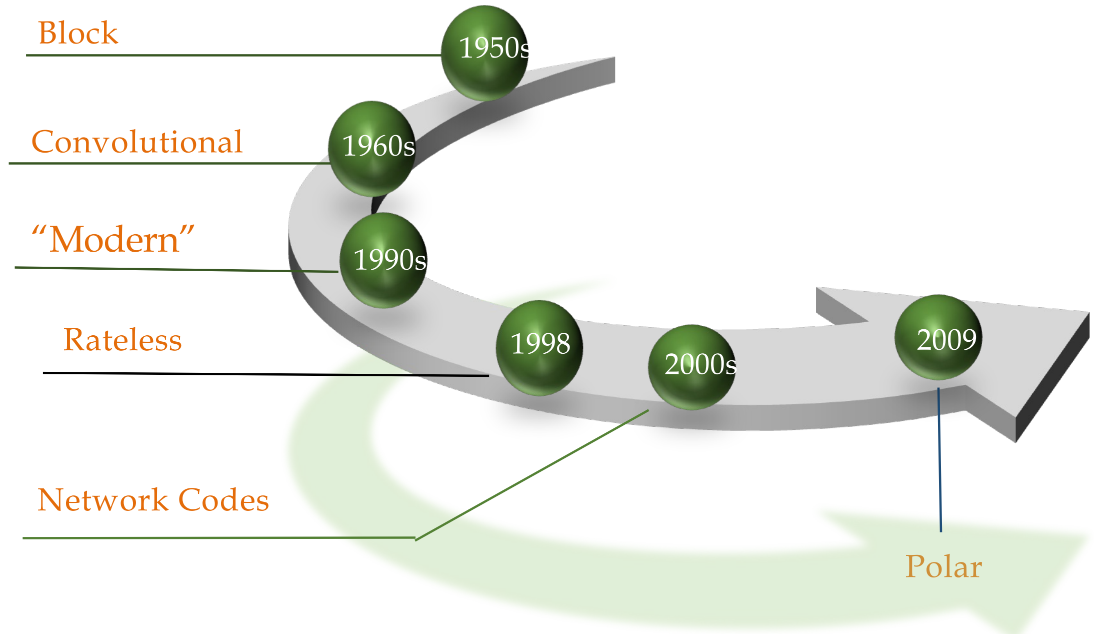


- When the data is read back or received **decoding** occurs
- **Soft information** improves accuracy but typically with extra complexity

Existing Paradigm: Co-design of Codes & Decoders



Decoder		Code
Error Detection Only	←	CRC
Majority Logic	←	RM
Berlekamp-Massey	←	BCH
CA-SCL	←	CA-Polar
No decoder	←	RLC



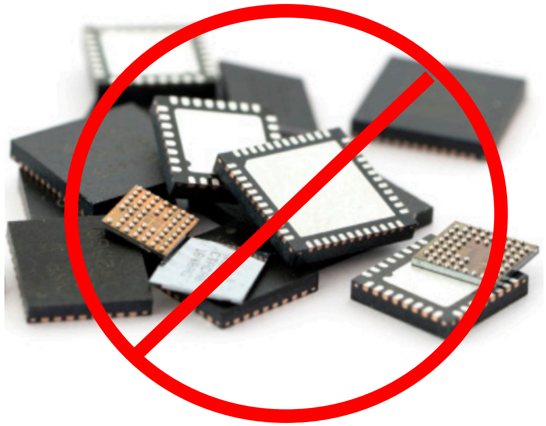
- **Distinct** software or hardware **algorithm** required to decode each code type.
- **Requires standardization** to ensure all devices have a decoder for the code being used.

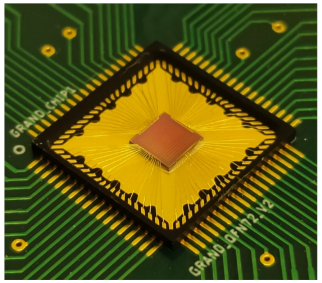
5G

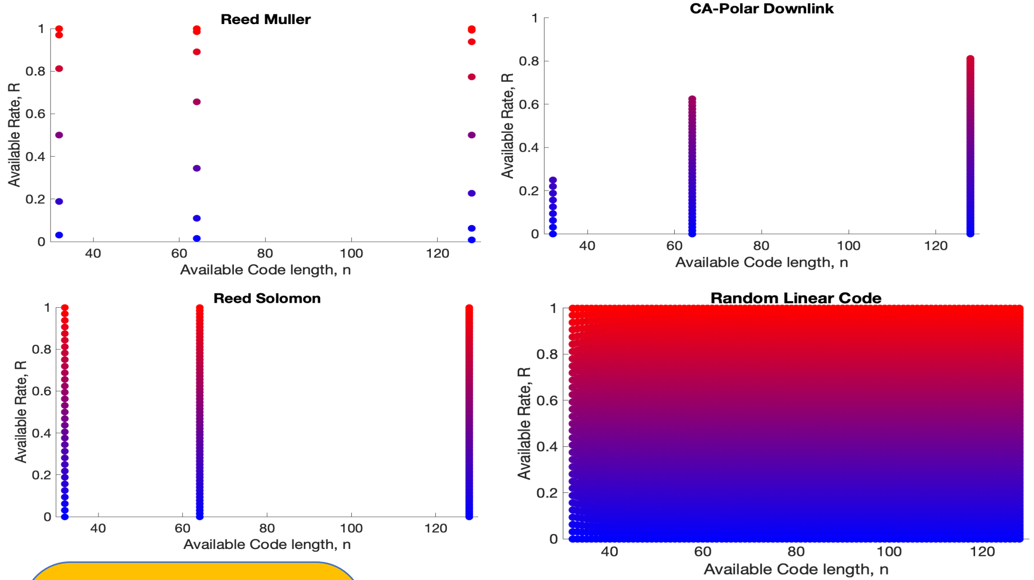
LDPC – 1960s
CA-Polar – 2010s

- E.g: **5G** technology mandates two types of codes be used.

Universal Decoding







Error Detection Only ← CRC →
Majority Logic ← RM →
Berlekamp-Massey ← BCH →
CA-SCL ← CA-Polar →
No decoder ← RLC →

GRAND™

granddecoder.mit.edu

Guessing Random Additive Noise Decoding

GRAND™ enable **optimally accurate** decoding of an **enormous class** of codes in an algorithm **proven** to be efficient implementation in **software** or **hardware**.

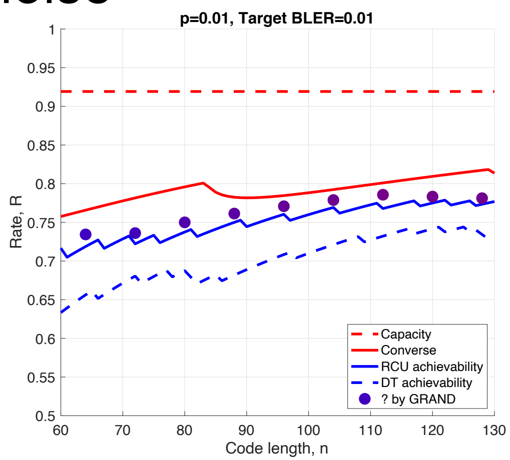
GRAND™

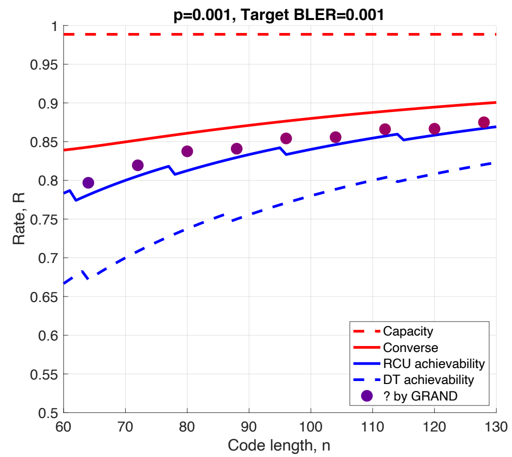
Guessing Random Additive Noise Decoding

Channel output is input plus noise

Standard decoder: identify X^n using structure of code-book
GRAND: identify N^n using structure of the noise

yp-mit/spect





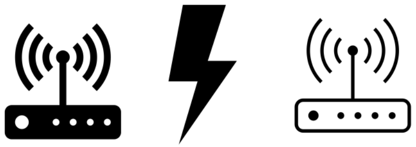
Inputs: code-book membership test, Y^n
Output: $c^{*,n}$, Q
$d \leftarrow 0$, $Q \leftarrow 0$.
while $d = 0$ **do**
  $z^n \leftarrow$ next most likely noise effect
  $Q \leftarrow Q + 1$
  if $Y^n \ominus z^n$ is in the code-book **then**
    $c^{*,n} \leftarrow Y^n \ominus z^n$
    $d \leftarrow 1$
    return $c^{*,n}$, Q
  end if
end while

- GRAND – hard detection
- **ORBGRAND – relative reliability soft info**
- Other variants

GRAND Duffy, Li & Medard, *IEEE ISIT*, 18; *IEEE Trans Inf Theory*, 19. **GRAND-MO** An, Medard, Duffy, *IEEE Trans Commun,* 22. **SRGRAND** Duffy & Medard, *IEEE ISIT*, 19; Duffy, Medard & An, *IEEE Trans Commun,* 21. **ORBGRAND** Duffy, Médard, An, IEEE Trans. Signal Proc., 21. **SGRAND** Solomon, Duffy & Medard, *IEEE ICC*, 20.

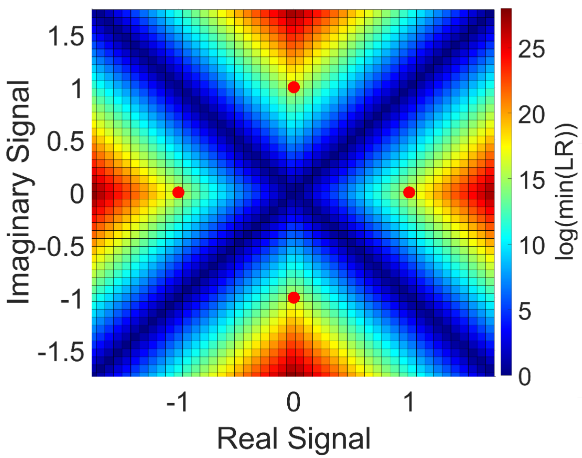
Decoding with Soft Information

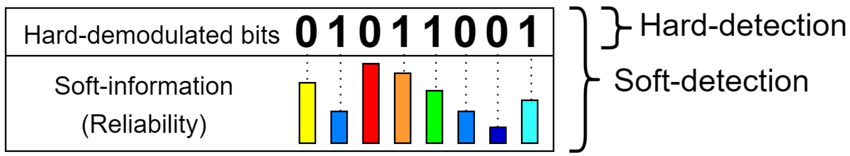
01100010

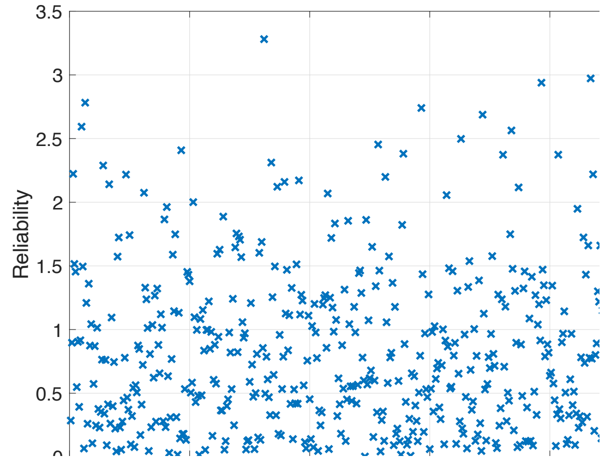


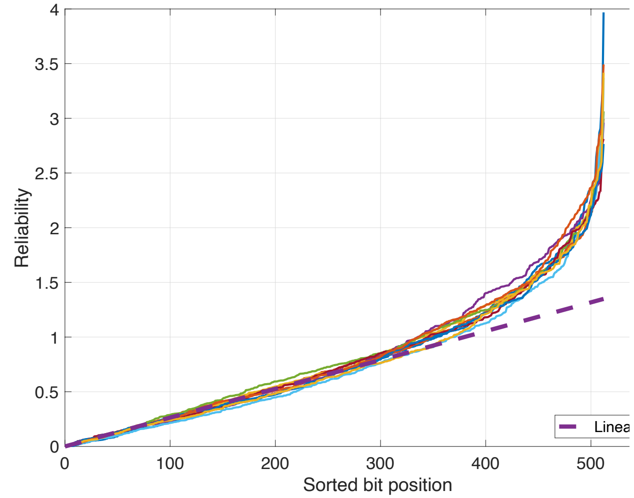
Soft Detection

11100011







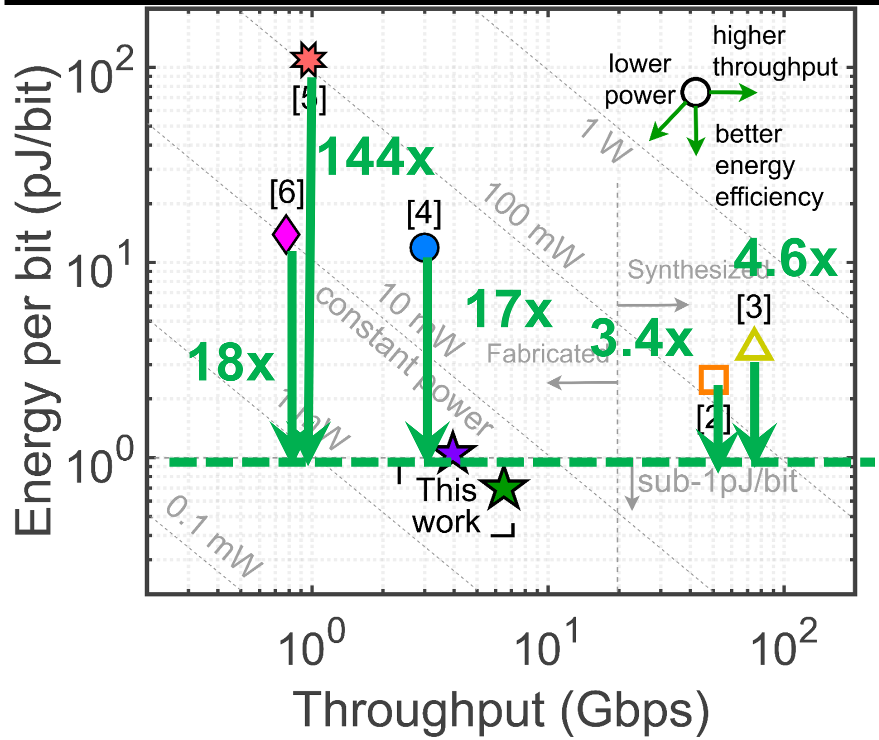


Ordered Reliability Bits - ORB

$$\mathrm{LLR}(Y_i) = \log \frac{\mathbb{P}(c_i = 1, Y_i)}{\mathbb{P}(c_i = 0, Y_i)}$$

Duffy, An, Médard, *IEEE Trans. Sig. Process.*, 23. Duffy, Médard, An, *IEEE Trans. Commun.*, 21. Duffy, *IEEE ICASSP,* 21. Solomon, Duffy, Médard, *IEEE ICC*, 20.

ORBGRAND in Hardware



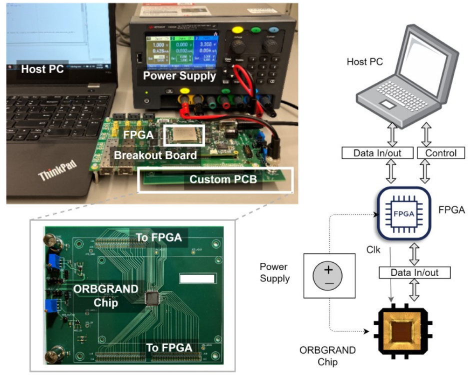
Riaz, Yasar, Ercan, An, Ngo, Galligan, Médard, Duffy, Yazicigil, *IEEE ISSCC, 23.*

Synthesized designs

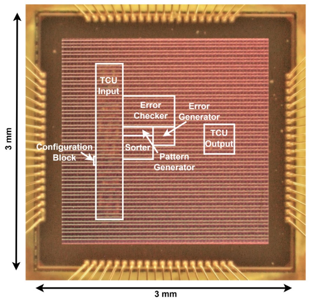
	[2]	[3]
Node:	65nm	7nm
Target FER:	10^{-7}	10^{-6}

Fabricated designs

	This work	This work	[4]	[5]	[6]
Node:	40nm	40nm	40nm	28nm	40nm
Target FER:	10^{-5}	10^{-7}	10^{-5}	10^{-5}	N.R.



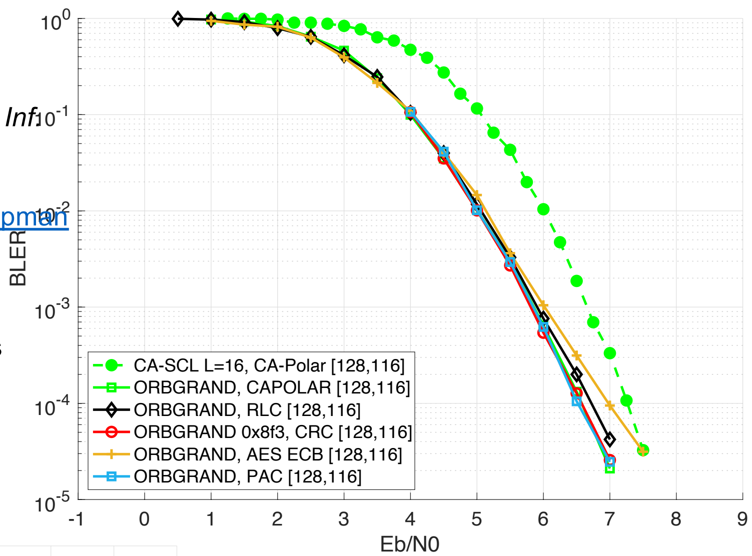
Reference	This Work		[2]	[3]	[4]	[5]	[6]
Sythesis/Fabricated	Fabricated		Synthesis	Synthesis	Fabricated	Fabricated	Fabricated
Technology (nm)	40		65	7	40	28	40
Code	CA-Polar/CRC (Universal)		CA-Polar (Universal)	BCH (Universal)	Polar	Polar	Polar
Algorithm	ORBGRAND		ORBGRAND	ORBGRAND	SCL	SCL	RNN-BP
Code Length	Up to 256		128	127	Up to 1024	1024	Up to 256
Supply (V)	1.0		0.9	0.5	0.9	1.05	0.9
Quantization (bits)	6		5	N.R.	6	6	5
Frequency (MHz)	90		454	616	430	413	225
Core Area (mm^2)	**0.4**		2.25	5.16	0.64	0.59	0.18
Target FER	10^{-5}	10^{-7}	10^{-7}	10^{-6}	10^{-5}	10^{-5}	N.R.
Power (mW)	**4.8**	**4.9**	133	277.6	42.8	101.4	12.8
Energy per bit (pJ/bit)	**1.14**	**0.76**	2.57	3.52	13.2	109.5	13.6
Latency (ns)	61.3	40.0	2.47	40.6	N.R.	1100	310
Throughput (Gbps)	4.3	6.5	51.8	78.85	3.25	0.93	0.82

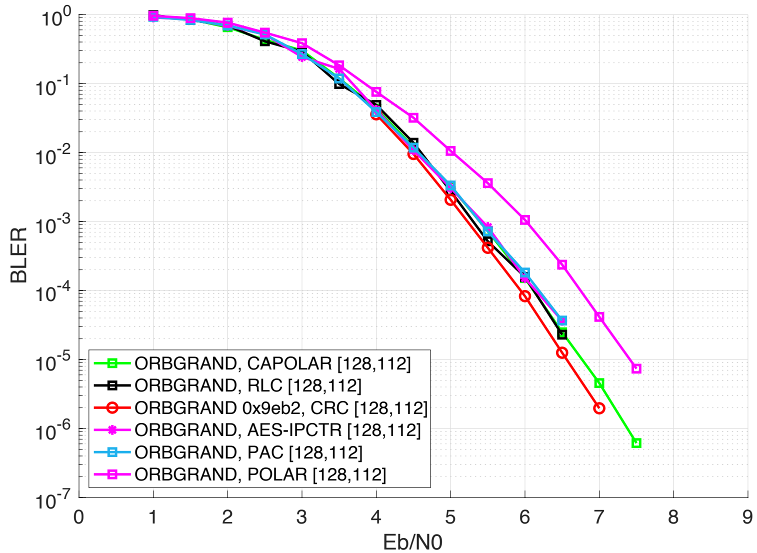


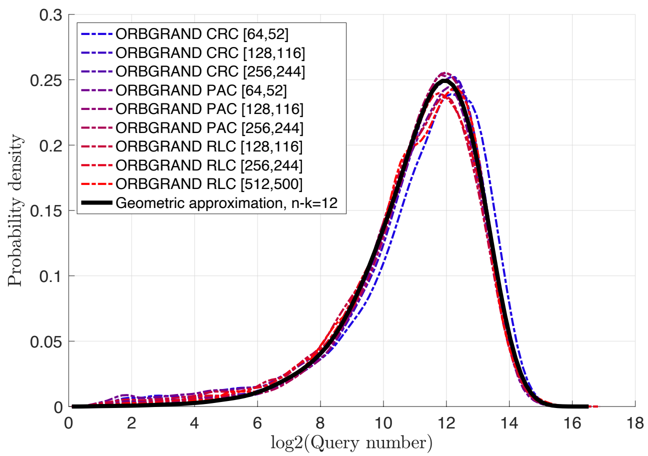
Chip implemented in TSMC 40 nm CMOS operating at 90 MHz clock frequency using a 1 V nominal power supply

Does Performance Depend on Code?

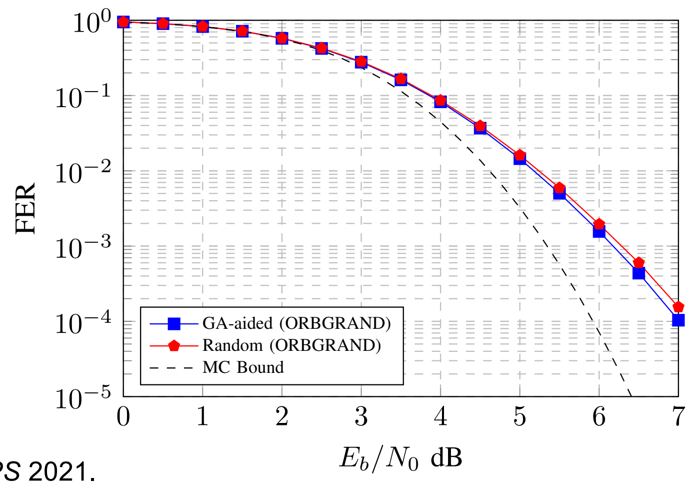
Coffey, Goodman, *IEEE Trans. Inf. Theory*, 90
Koopman, https://users.ece.cmu.edu/~koopman/crc/ CRCs
Cohen, D'Oliveira, Duffy, Woo, Médard, *IEEE Coms Letters 23*
Arikan, *arXiv*, 2019, PAC codes







Performance and complexity with ORBGRAND for different codes depends on (n,k)



Papadopoulou, Hashemipour-Nazari, Balatsoukas-Stimming, *SiPS* 2021.

Confident Decoding – Forney 1968

Can you determine the likelihood a decoding is correct?

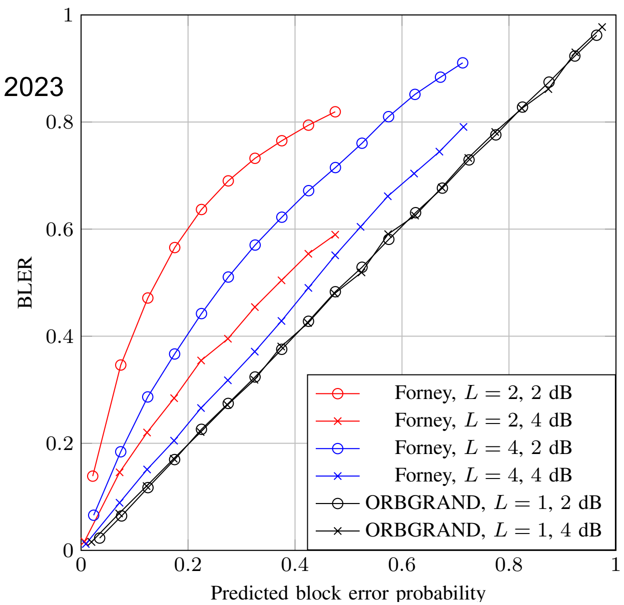
For Forney's approach, need at least two decodings for approximation. $\frac{p(c^{*,n}|Y^n)}{\sum_{c^n} p(c^n|Y^n)}$

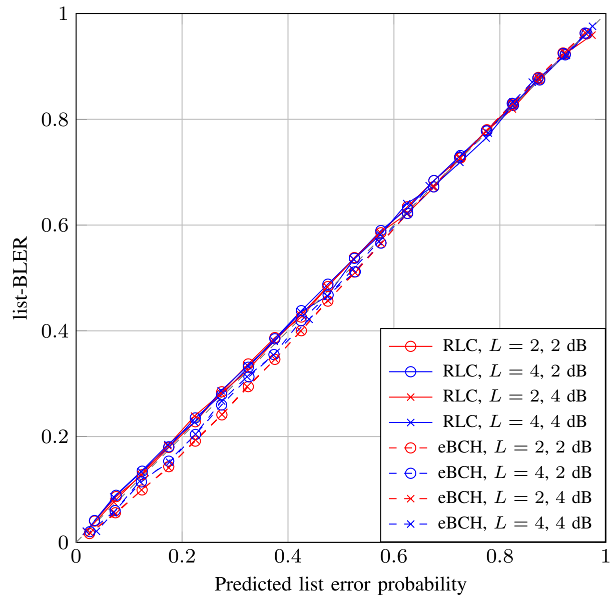
Forney, *IEEE Trans. Info. Theory,* 68.

For GRAND: $\text{Prob. decoding correct} = \frac{\text{Prob. noise effect found}}{\text{Prob noise effect found + prob incorrect found}}$

Galligan, Medard, Duffy, *CISS*, 23
Galligan, Yuan, Medard, Duffy, *Arxiv* 2023

Only GRAND provides this reliability estimate





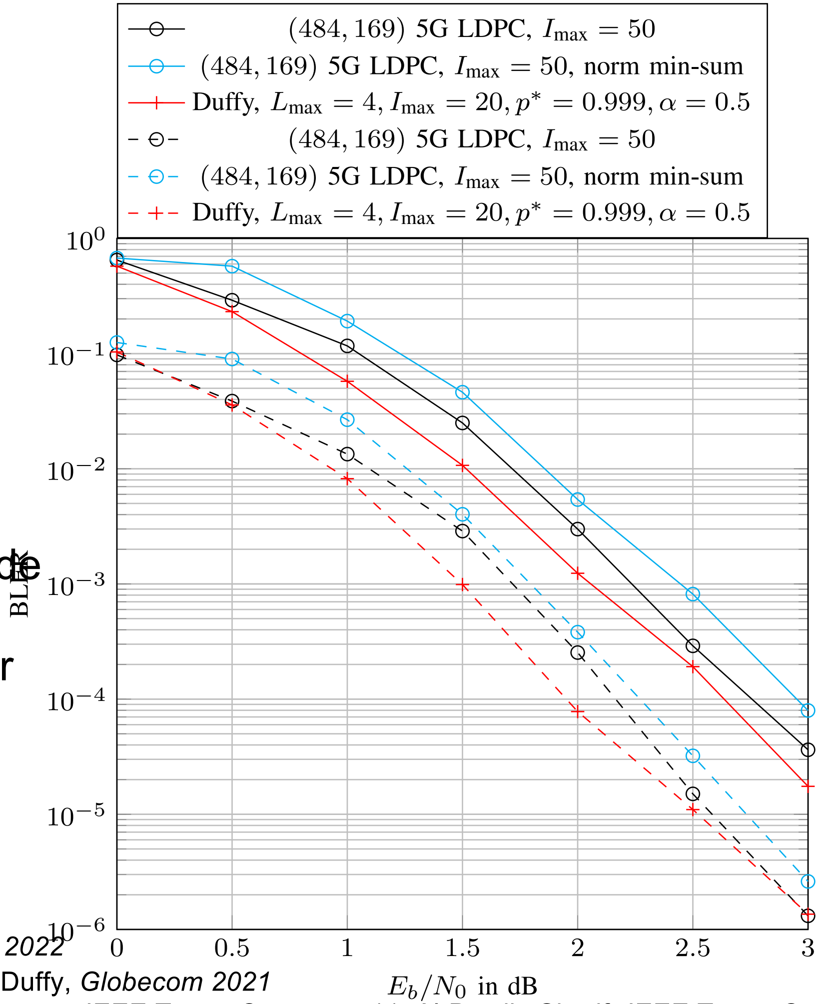
Reliability - Product Codes to Outperform 5G LDPCs

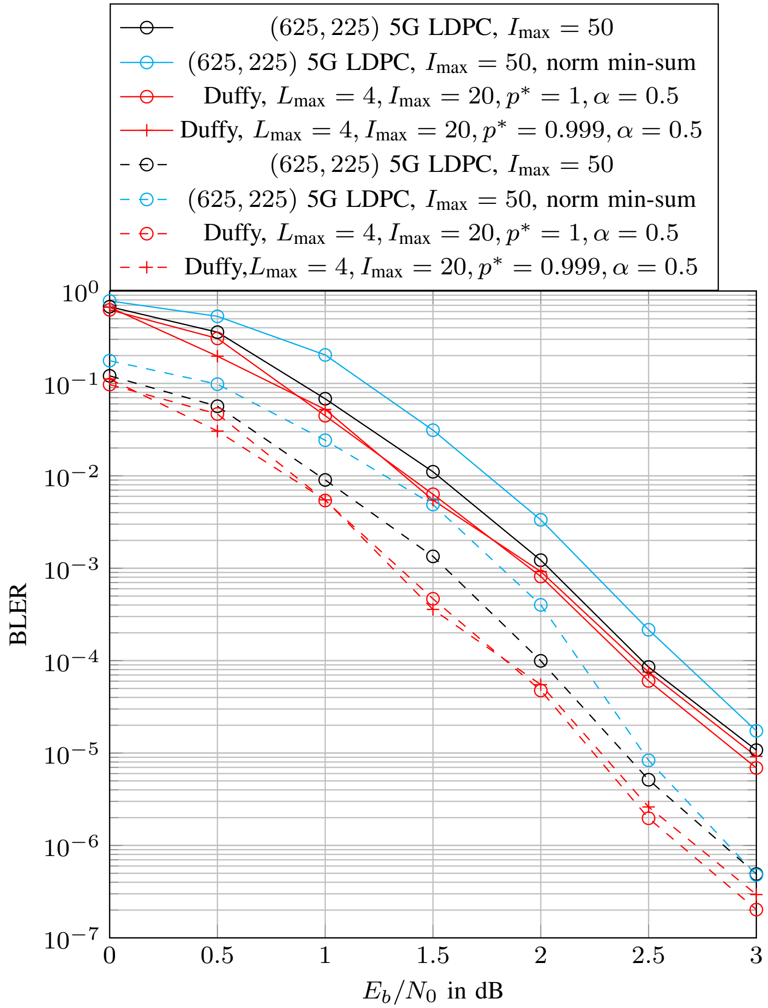
GRAND as component decoder

u_1	u_2	u_3	p_1	p_2
u_4	u_5	u_6	p_3	p_4
u_7	u_8	u_9	p_5	p_6
p_7	p_9	p_{11}	p_{13}	p_{15}
p_8	p_{10}	p_{12}	p_{14}	p_{16}

Long, low-rate codes are made from short, high-rate codes.

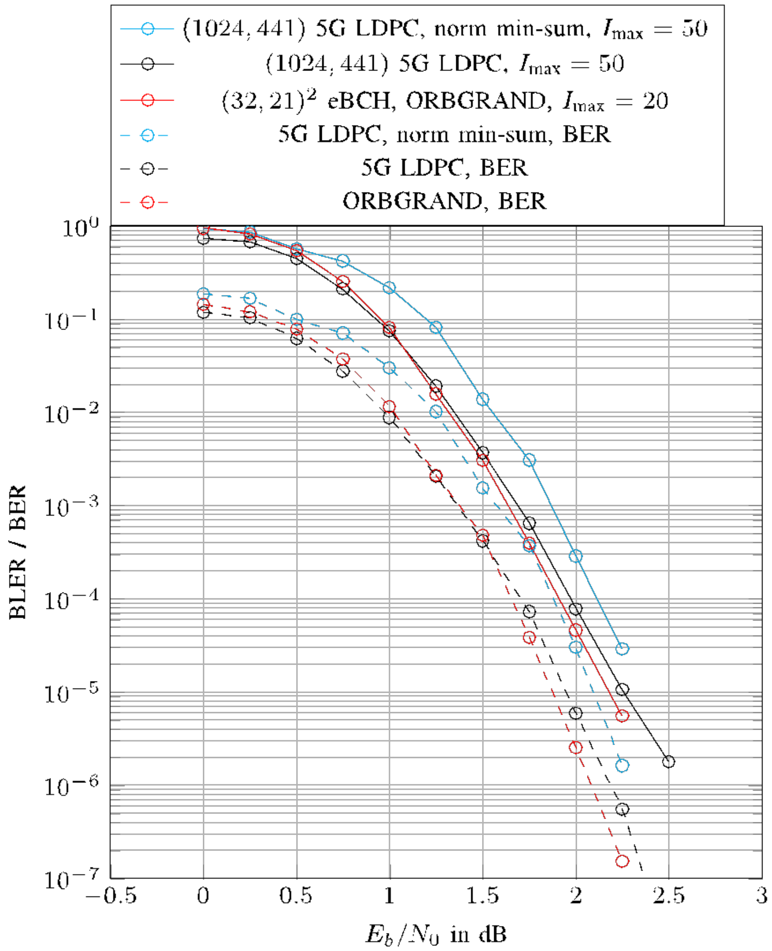
- Single component decoder for reduced footprint.
- Allow parallelization with multiple decoders for reduced latency.

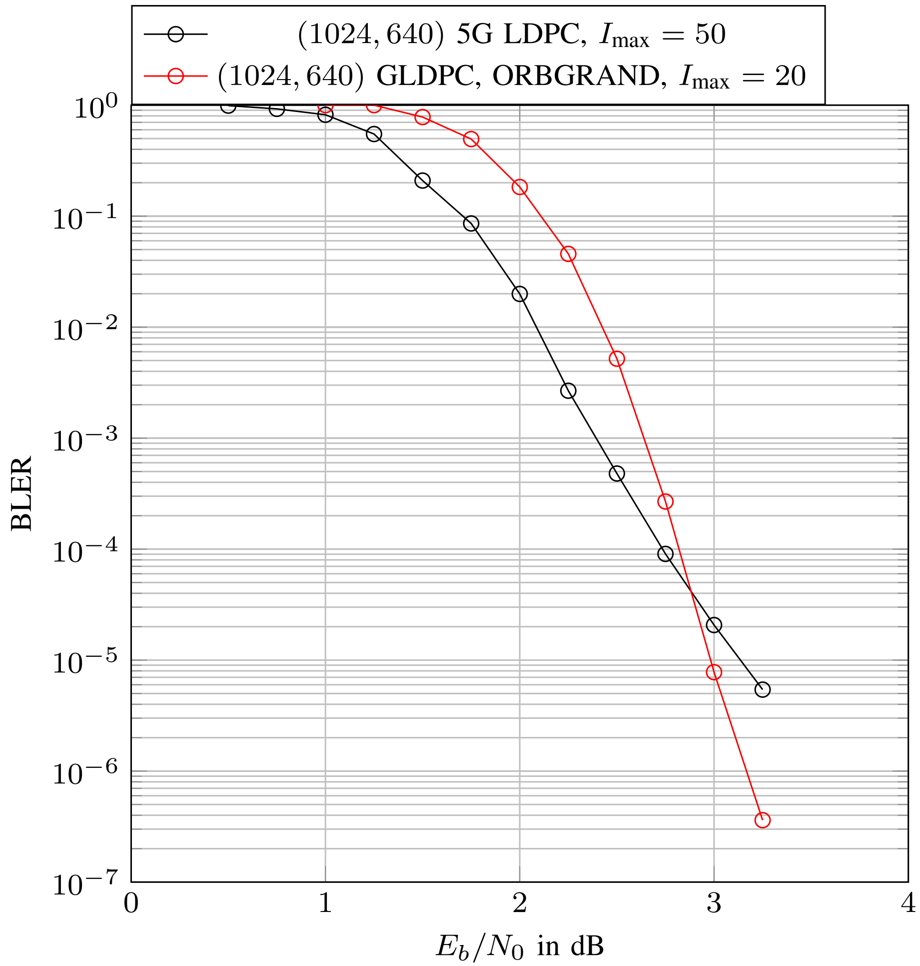


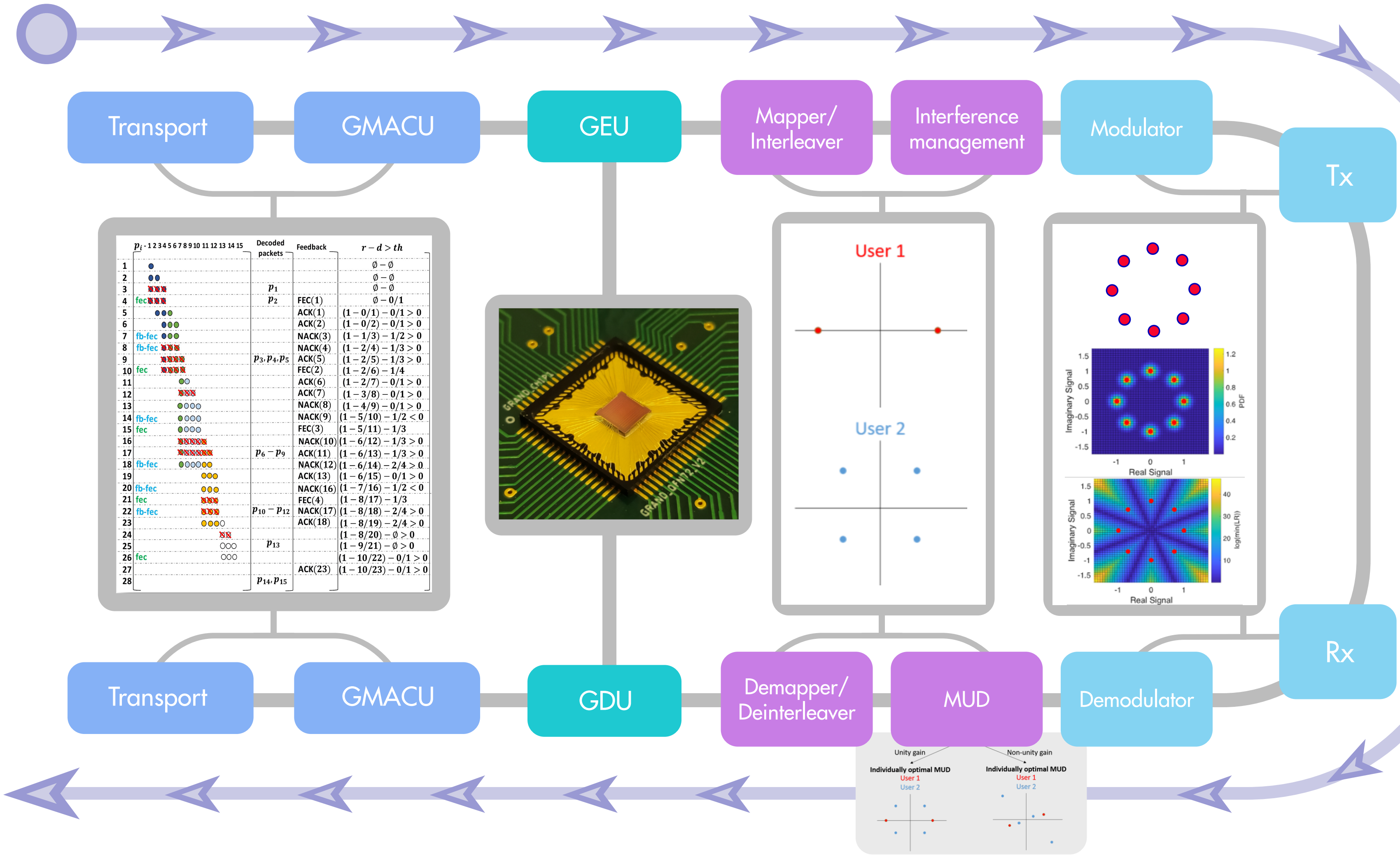


Galligan, Médard, Duffy, *CISS* 2023
Riaz, Médard, Duffy, Yazicigil, *COMSNETS 2022*
Galligan, Solomon, Riaz, Médard, Yazicigil, Duffy, *Globecom 2021*
Hager, Pfister, *IEEE Trans. Commun.*, 18. Justesen *IEEE Trans. Commun.*, 11. Al-Dweik, Sharif, *IEEE Trans. Commun.*, 09. P. Elias, Trans. *IRE Prof. Group Inf. Theory*, 54

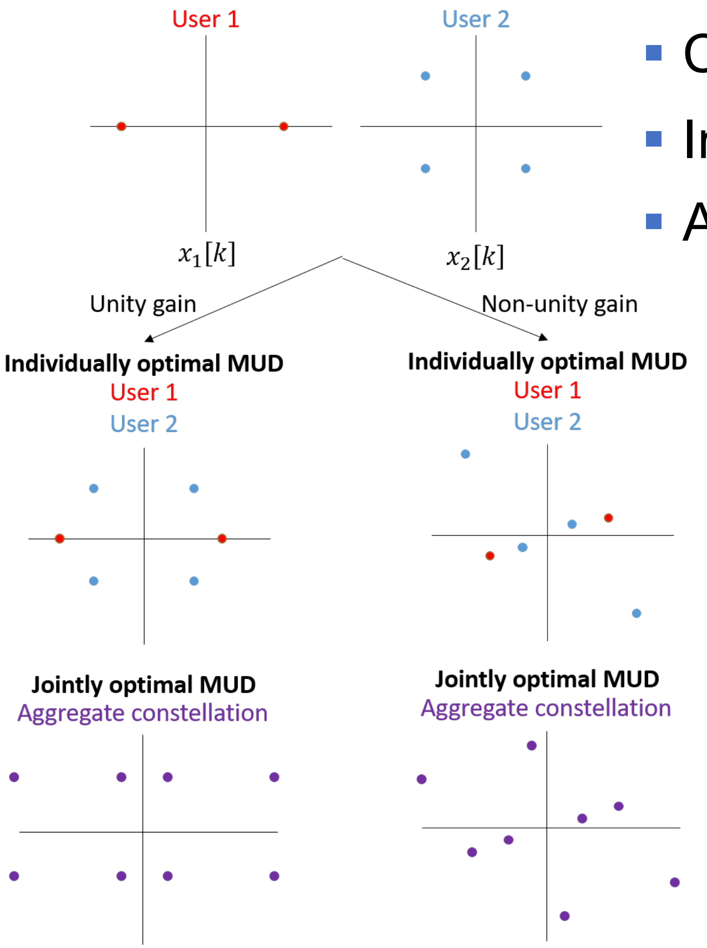
Revisiting Old Codes with GRAND



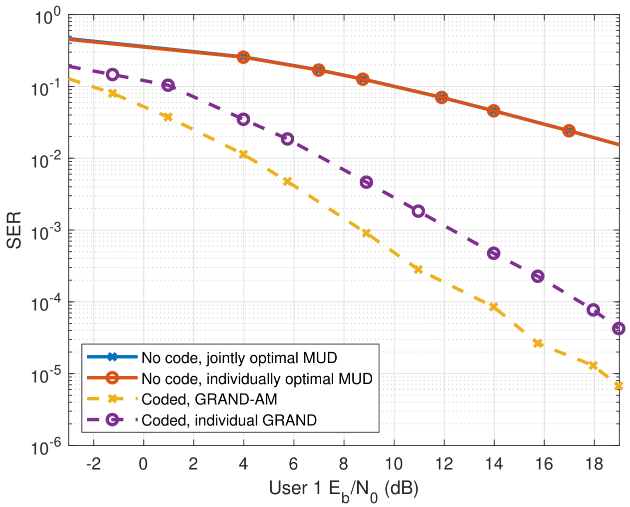


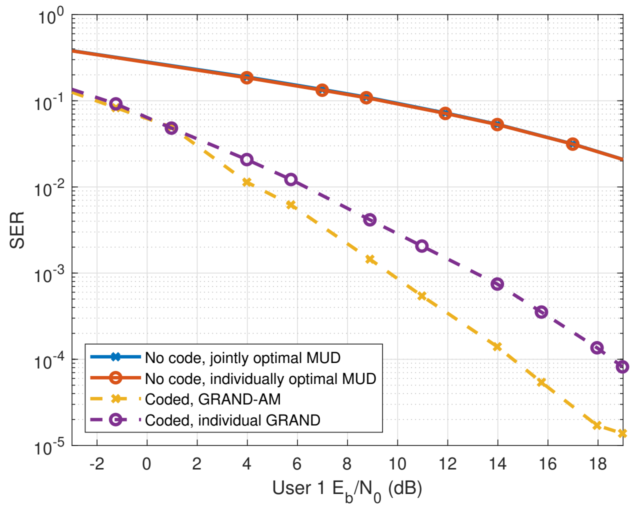

Transport
GMACU
GEU
Mapper/
Interleaver
Interference
management
Modulator
Tx
User 1
User 2
Imaginary Signal
Real Signal
PDF
Rx
Transport
GMACU
GDU
Demapper/
Deinterleaver
MUD
Demodulator
Unity gain
Non-unity gain
Individually optimal MUD
User 1
User 2
Individually optimal MUD
User 1
User 2

Multiple Access



- Consider multiple access as a larger constellation
- In that constellation, users share the symbols
- A short (8,4) CRC can give each user half the bandwidth



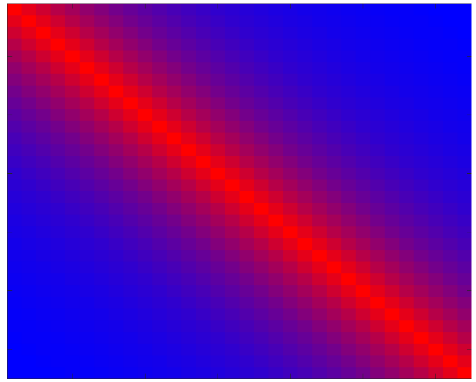


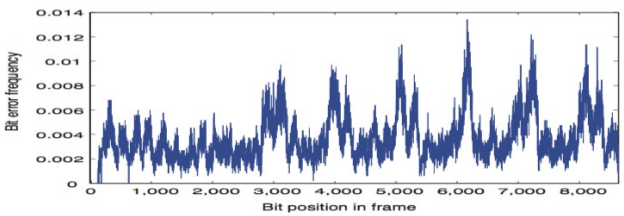
Interleaving

Interleaving can only increase noise entropy

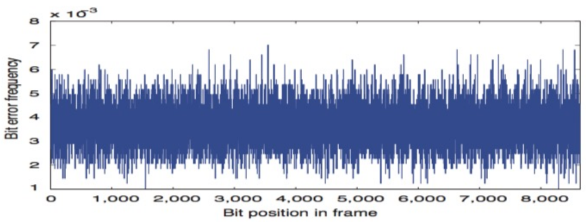
$$C_{i,j} = \sigma^2 \rho^{|i-j|}$$

Correlation matrix





(a) Before interleaving



(b) After interleaving

IEEE matrix interleaver
Chen & Leith, *IEEE ICC* 2015

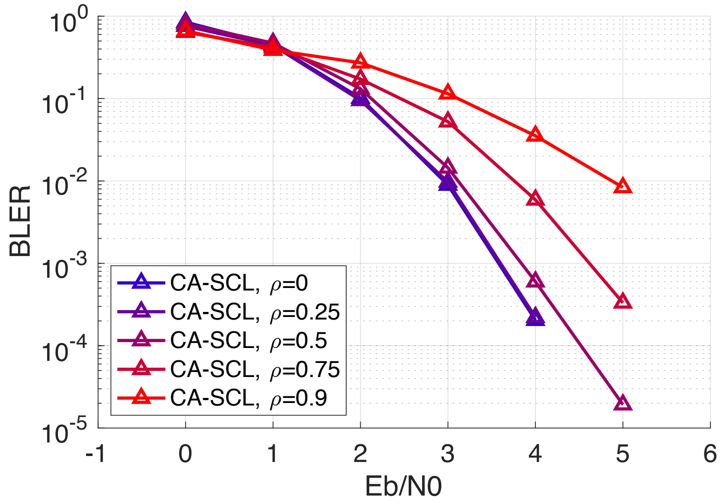
Collect data as rows:

$$\begin{pmatrix} c_{1,1} & c_{1,2} & c_{1,3} & \cdots & c_{1,n-1} & c_{1,n} \\ \hline c_{2,1} & c_{2,2} & c_{2,3} & \cdots & c_{2,n-1} & c_{2,n} \\ \hline \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\ \hline c_{n,1} & c_{n,2} & c_{n,3} & \cdots & c_{n,n-1} & c_{n,n} \end{pmatrix}$$

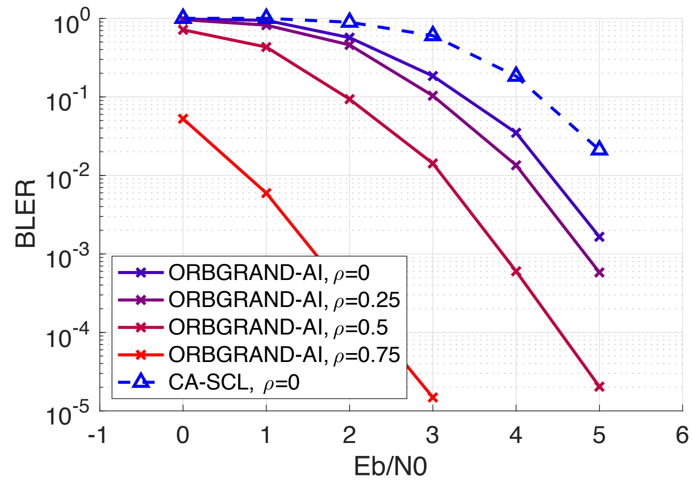
Transmit as columns:

$$\left(\begin{array}{c|c|c|c|c|c} c_{1,1} & c_{1,2} & c_{1,3} & \cdots & c_{1,n-1} & c_{1,n} \\ c_{2,1} & c_{2,2} & c_{2,3} & \cdots & c_{2,n-1} & c_{2,n} \\ \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\ c_{n,1} & c_{n,2} & c_{n,3} & \cdots & c_{n,n-1} & c_{n,n} \end{array}\right)$$

What Happens if We Don't Interleave?

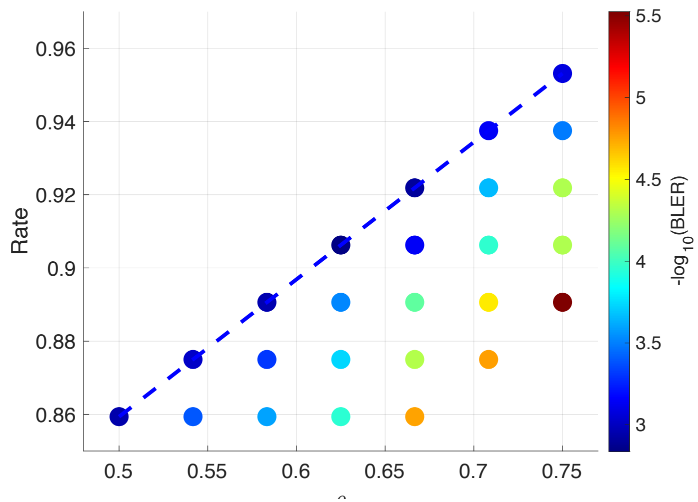


CA-Polar [128,64], rate 1/2

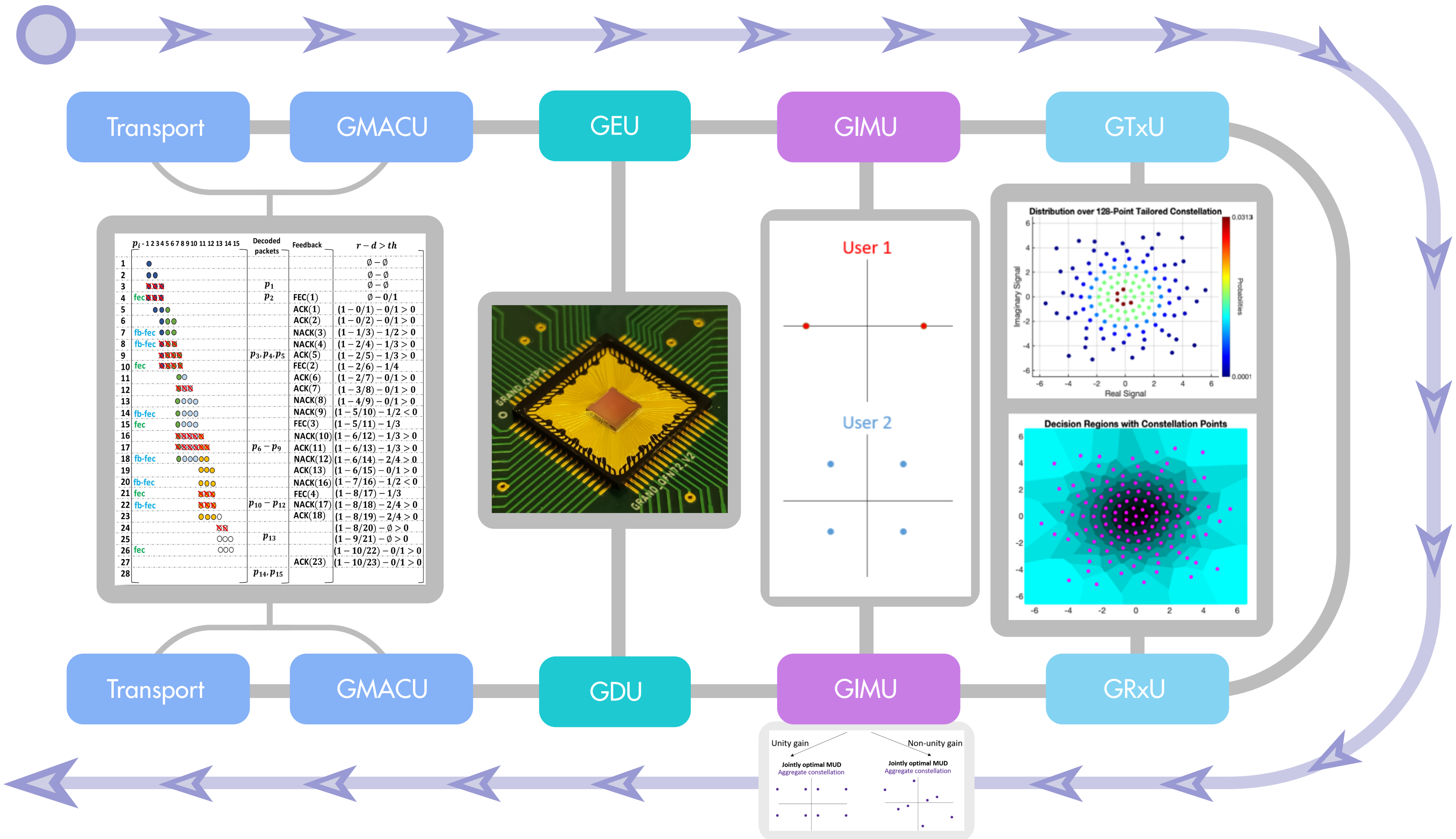


CA-Polar[128,110], rate 0.86

What code-rate can we use to meet the interleaved benchmark of BLER of 10^{-3} at 3.7dB achieved by CA-SCL with a rate ½ [128,64] code?

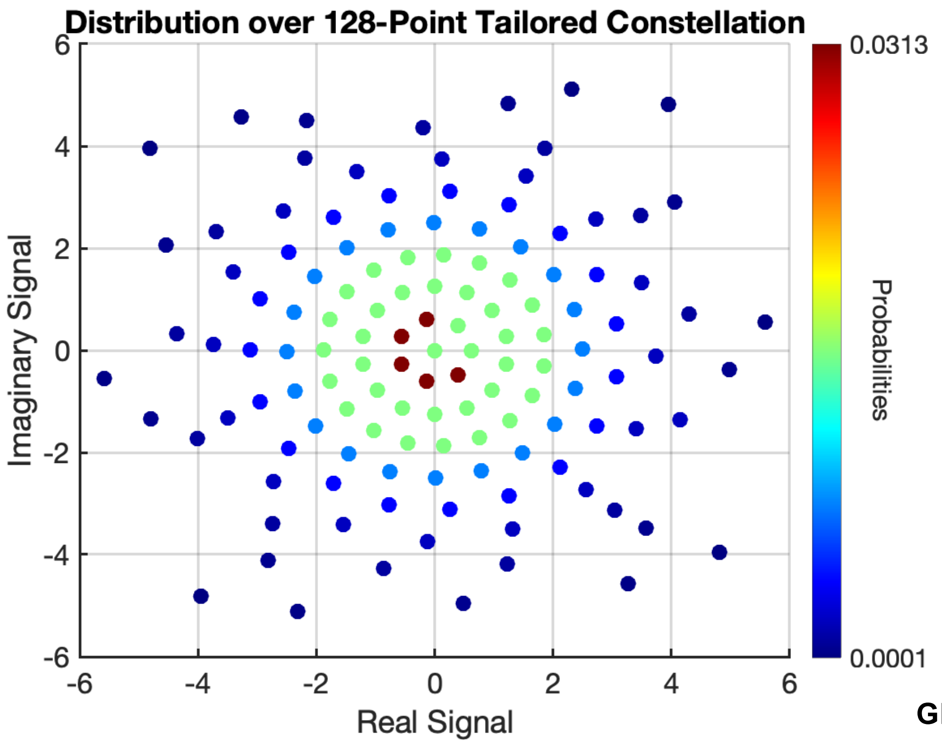


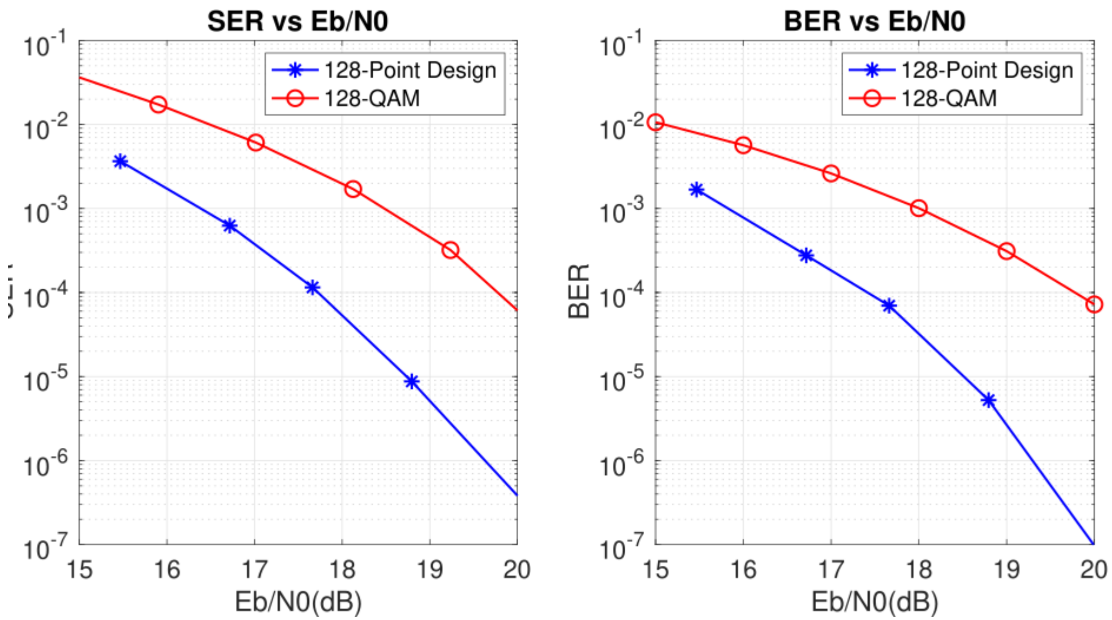
Duffy, Grundei, Médard, arXiv, 2023, to appear Globecom 2023


Transport
GMACU
GEU
GIMU
GTxU
User 1
User 2
Distribution over 128-Point Tailored Constellation
Imaginary Signal
Real Signal
Probabilities
Decision Regions with Constellation Points
Transport
GMACU
GDU
GIMU
GRxU
Unity gain
Non-unity gain
Jointly optimal MUD
Aggregate constellation
Jointly optimal MUD
Aggregate constellation

Optimized Modulation

We use length as a check and GRAND to manage insertions/deletions in variable length codes





GRAND-assisted Optimal Modulation , Ozaydin, Medard, Duffy, *IEEE GLOBECOM*, 22.

Modularity

- Standards currently lead to costly inefficiencies
- Complexity requires modularity to enable compatibility with adaptability
- Role of standards can move to creating APIs instead of monolithic systems

Acknowledgement

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- This work was sponsored, in part, by the National Science Foundation (NSF).
- The content of the information does not necessarily reflect the position or the policy of the US Government, and no official endorsement should be inferred.