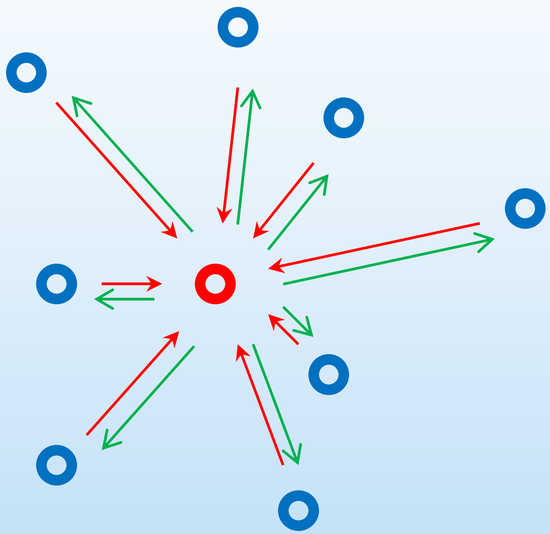
COMPUTER & ELECTRONIC ENGINEERING

Multiplexing
Multiple Access

Wireless communication

- Open, broadcast, unreliable medium
- Security issues
- Reliability issues
- Medium sharing issues

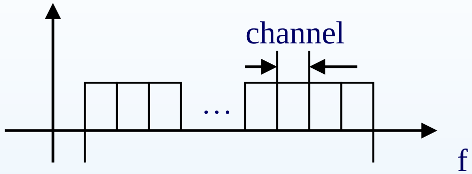
Multiple access/multiplexing



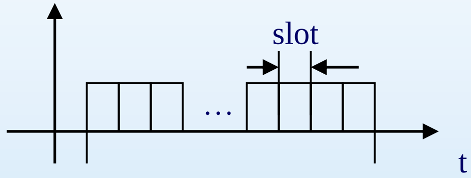
- Star topology: many independent users access the wireless communication medium to transmit to a common receiver (multiple access).
- A simultaneous transmission may be destructive (collision).
- Destructive collisions should be avoided (otherwise the information has to be recovered through repetition).
- Multiplexing: the common receiver replies also through the wireless channel, adopting a suitable resource sharing technique.

Multiplexing

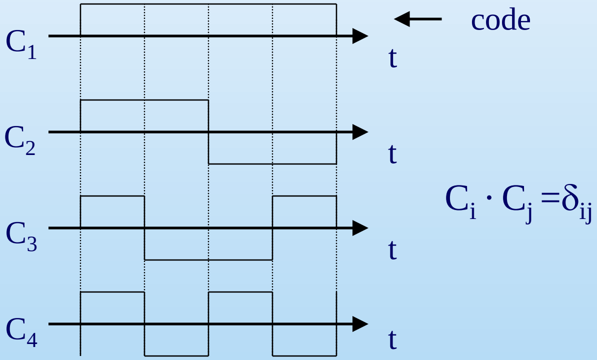
- Frequency Division Multiplexing (FDM) / Frequency Division Multiple Access (FDMA): different transmitters use different frequencies (1G, 2G, 4G).



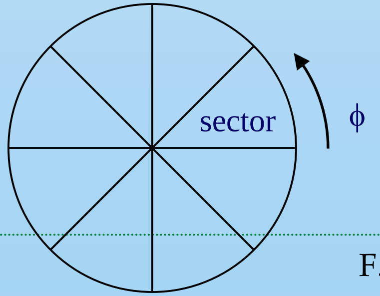
- Time Division Multiplexing (TDM) / Time Division Multiple Access (TDMA): different users transmit at different times (2G, 4G).



- Code Division Multiplexing (CDM) / Code Division Multiple Access (CDMA): different transmitters use different codes (3G).



- Space Division Multiplexing (SDM) / Space Division Multiple Access (SDMA): space separation through beamforming (2G, 3G, 4G).



Orthogonal Frequency Division Multiplexing

- M*ulti-path* channel:

$$h(t,\tau)=\sum_{l=0}^{L-1} h_l(t)\delta(\tau-\tau_l)$$

- OFDM: Let W be the available bandwidth. I divide the signal (complex envelope) into N flows that occupy a bandwidth equal to $\Delta f = W/N < B_c$ (Coherence Band). Let $S_n[k]$ be the modulation symbols in use.

$$\tilde{s}(t)=\sum_{n=-\infty}^{\infty}\sum_{k=0}^{N-1} S_n[k]g(t-nT)e^{j2\pi(k-N/2)\Delta f t}$$

- Orthogonality conditions among the carriers: $\Delta f = 1/T$.
- Be $g(t)$=rect(t/T-1/2). In [0,T) we have: $\tilde{s}(t)=\sum_{k=0}^{N-1} S[k]e^{j2\pi(k-N/2)t/T}$
- Since the positive half-band is equal to $W/2$ we can sample with a sampling interval equal to $1/W=T/N$. The samples are:

$$\tilde{s}[m]=\tilde{s}\left(t=m\frac{T}{N}\right)=\sum_{k=0}^{N-1} S[k]e^{j2\pi(k-N/2)m/N}=\sum_{k=0}^{N-1} S_{\text{shift}}[k]e^{j2\pi mk/N}=N\ \text{IDFT}\{S_{\text{shift}}[k]\}$$

OFDM: Transmission algorithm

- $\mathbf{S} = [S[-N/2], S[-N/2+1], \ldots, S[0], .., S[N/2]]$. Usually $S[0]$=0.
- Defined $N_{\mathrm{FFT}}=2^K$, we add N_{FFT} - N zeros -1 (*zero padding*)

$$\mathbf{S}_{\mathrm{PADD}} = [S[-N/2], S[-N/2+1], \ldots, S[0]=0, .., S[N/2], 0, \ldots, 0]$$

- $\mathbf{S}_{\mathrm{SHIFT\text{-}PADD}} = [0, S[1], \ldots, S[N/2], 0, \ldots, 0, S[-N/2], \ldots, S[-1]]$
- IFFT: $\tilde{\mathbf{s}} = [\tilde{s}[0], \tilde{s}[1], \ldots, \tilde{s}[N_{FFT}-1]]$
- Added cyclic prefix (CP: Cyclic Prefix), replicating at the top of the sample vector the last L-1 samples, where L is the length of the channel impulse response).

$$\tilde{\mathbf{s}}_{\mathrm{CP}} = [\tilde{s}[N_{FFT}-L+1], \ldots, \tilde{s}[N_{FFT}-1]]$$

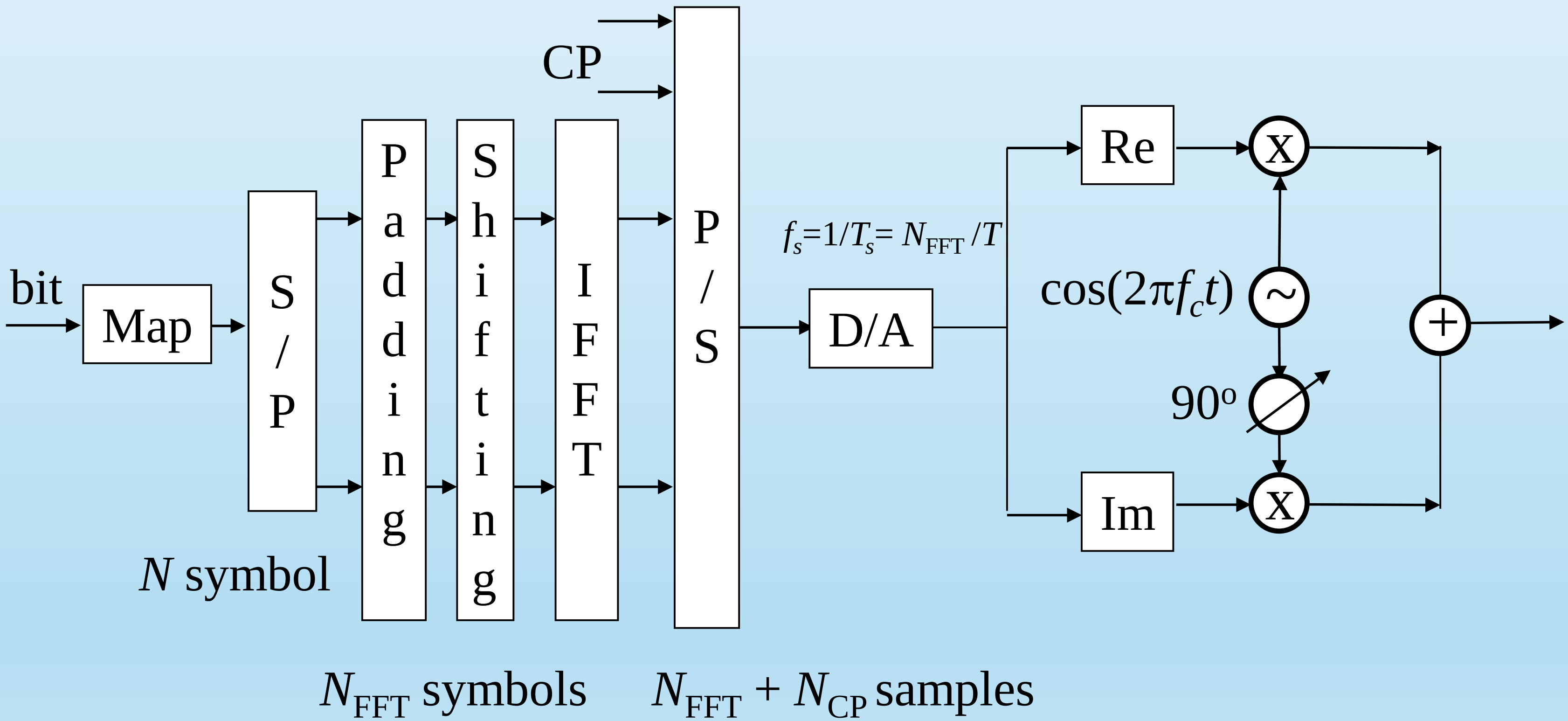
- Parallel to series conversion and transmission.

Cyclic Prefix (CP)

- The receiver's task is to calculate the DFT of the received signal in NFFT values.
- By prefixing the transmitted symbol vector with the last *L*-1, the channel response (obtained by linear convolution) contains the samples that allow the direct calculation of the DFT. That is, it results in (distinct samples see distinct and independent carriers).
- Example (*L*=3, NFFT =4).

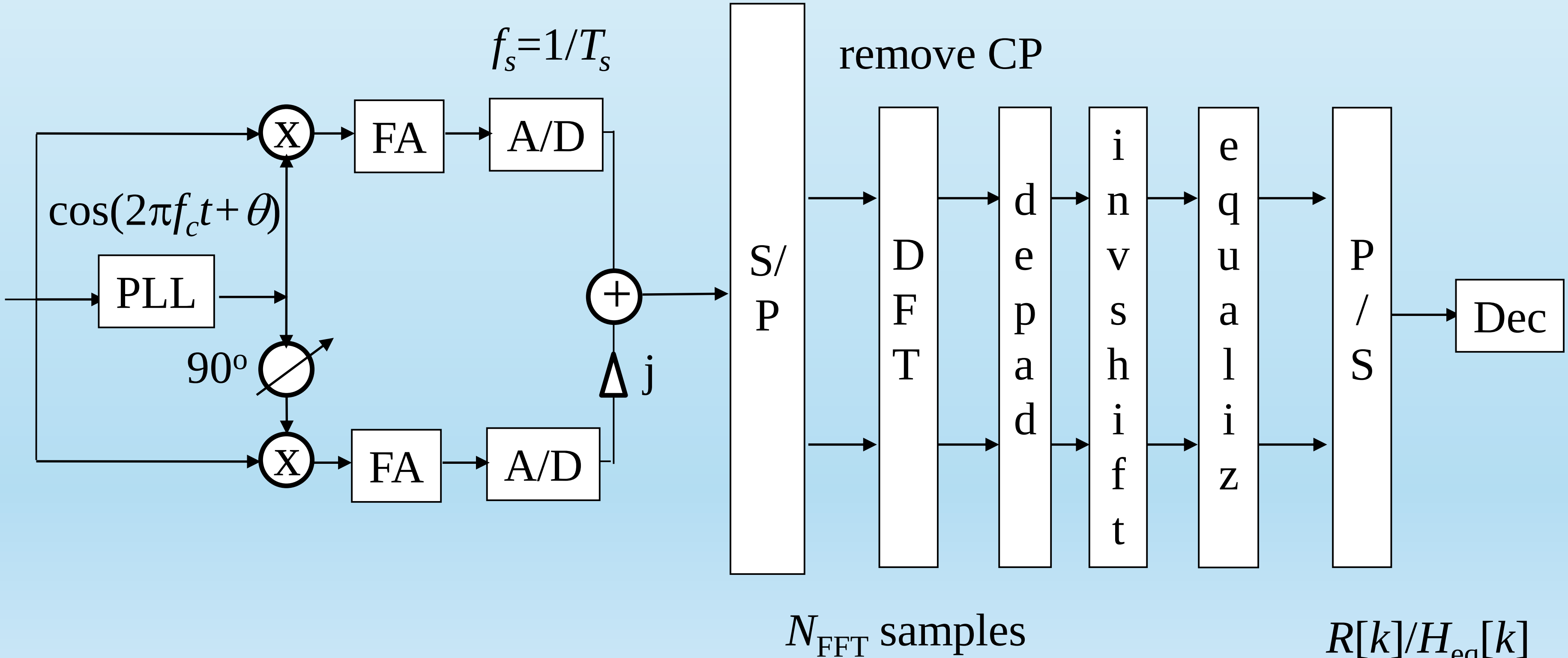
CP_{S1}		S_1				CP_{S2}		S_2	Y_n	Cyclic convolution
S_{12}	S_{13}	S_{10}	S_{11}	S_{12}	S_{13}	S_{22}	S_{23}	S_{20}		
h_2	h_1	h_0							y_{10}	$S_{12}\,h_2 + S_{13}\,h_1 + S_{10}\,h_0$
	h_2	h_1	h_0						y_{11}	$S_{13}\,h_2 + S_{10}\,h_1 + S_{11}\,h_0$
		h_2	h_1	h_0					y_{12}	$S_{10}\,h_2 + S_{11}\,h_1 + S_{12}\,h_0$
			h_2	h_1	h_0				y_{13}	$S_{11}\,h_2 + S_{12}\,h_1 + S_{13}\,h_0$
				h_2	h_1	h_0			CP_{R1}	
					h_2	h_1	h_0			
						h_2	h_1	h_0	y_{20}	$S_{22}\,h_2 + S_{23}\,h_1 + S_{20}\,h_0$

Transmitter



Receiver

- The equalizer block restores the starting constellation, inverting the channel (CSI), hypothetically flat in the band occupied by the sub-carrier – flat fading, coherent demodulation.



OFDM - summary

- The transmission, which is broadband overall, uses an adequate number of parallel narrowband channels, affected by flat fading.
- Channel compensation occurs in the frequency domain (coherent demodulation).
- Efficient modulation and demodulation operating in discrete time using IFFT and FFT.
- Optimal use of the band and channel using adaptive techniques (water filling).

- Observations
  - The channel must be reasonably flat in the band occupied by the subcarrier.
  - Efficiency is partially reduced by the (essential) use of the cyclic prefix.

Orthogonal Time Frequency Space (OTFS)

- Orthogonal Time Frequency Space (OTFS) is a multiplexing technique that carries the information in the Delay-Doppler coordinate system.
- The information is transformed in the similar time-frequency domain as utilized by the traditional schemes of modulation such as TDMA, CDMA, and OFDM
- It was first used for fixed wireless, and is now a contending waveform for 6ext generation networks due to its robustness in high-speed vehicular and mobile satellite scenarios.
- High mobility scenarios, such as fast-moving vehicles or dynamic wireless networks, introduce severe channel impairments due to rapid time-varying fading, Doppler shift, and time dispersion. OFDM, with its fixed orthogonal subcarriers, struggles to cope with severe channel variations. As a result, the performance of OFDM degrades significantly, leading to reduced data rates and increased error rates.

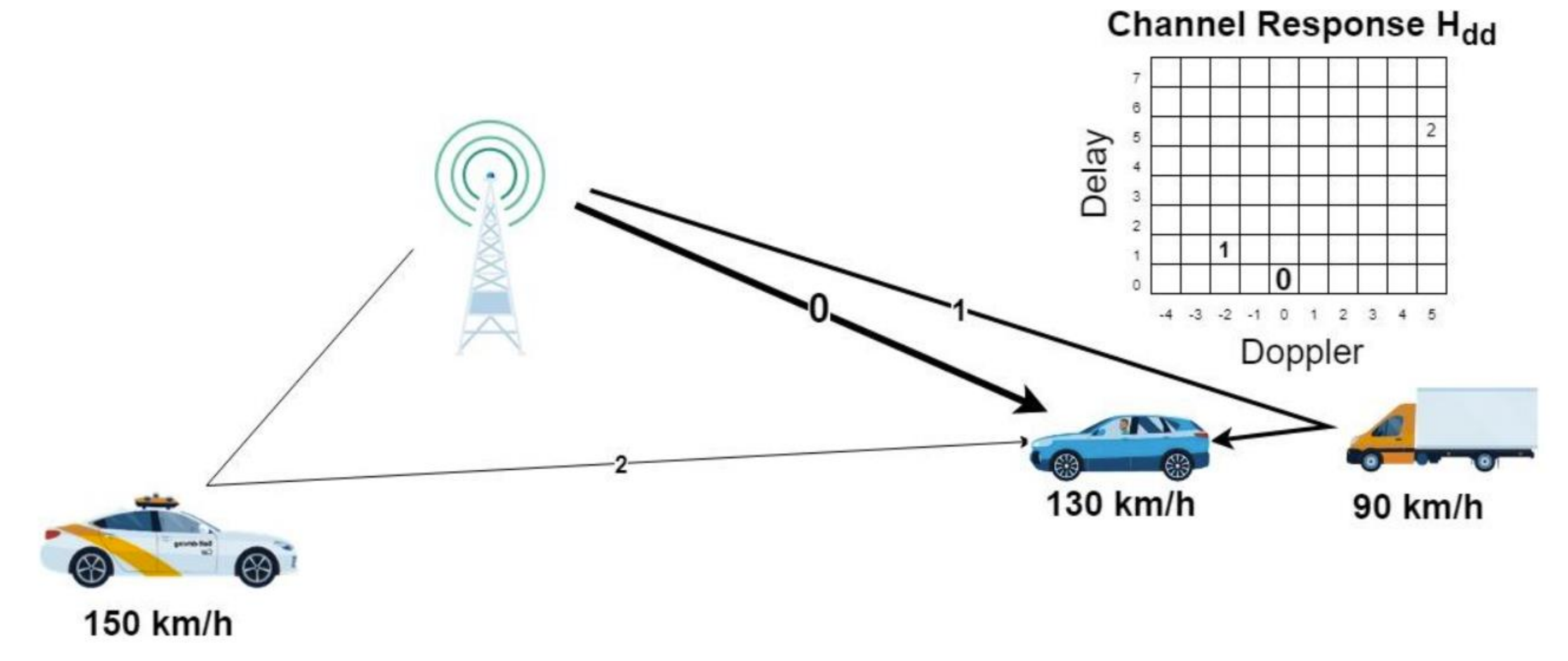
- A. Monk, R. Hadani, M. Tsatsanis, S. Rakib, "OTFS - Orthogonal Time Frequency Space". arXiv:1608.02993, 2016-08-09.

Orthogonal Time Frequency Space (OTFS)

- "OTFS is a new air interface paradigm with important spectral efficiency advantages in high order MIMO and high Doppler scenarios. OTFS also provides efficiency in pilot packing of reference signals for channel estimation and prediction. All reference signals and modulation symbols are carried in the Delay-Doppler domain and experience the same channel response over the transmission /observation interval and extract the maximum diversity of the channel in both time and frequency dimensions. This allows the FEC layer to operate on a signal with a uniform Gaussian noise pattern, regardless of the particular channel structure. OTFS has a natural architectural compatibility with OFDM, based on its underlying multicarrier components. Moreover, the reference signal architecture supports any form of multicarrier modulation.
- 3GPP has identified a variety of eMBB deployment scenarios that focus on high vehicle speed and massive MIMO antenna arrays. The new radio air interface must support high spectral efficiency in high Doppler environments while supporting a large number of antennas. OTFS is ideally suited for these requirements, providing: high spectral efficiency; accurate channel estimation and prediction; and very efficient and flexible reference signals for massive MIMO applications."

Orthogonal Time Frequency Space (OTFS)

- Mobile scatterer signal arrives delayed and on a different carrier frequency



- https://it.mathworks.com/help/comm/ug/otfs-modulation.html

Orthogonal Time Frequency Space (OTFS)

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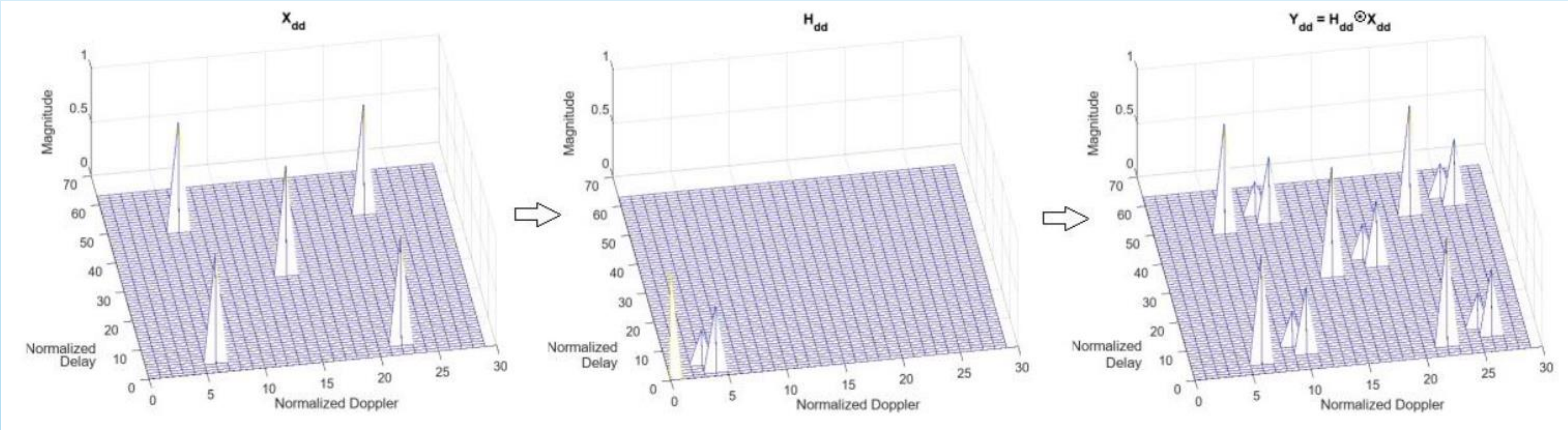
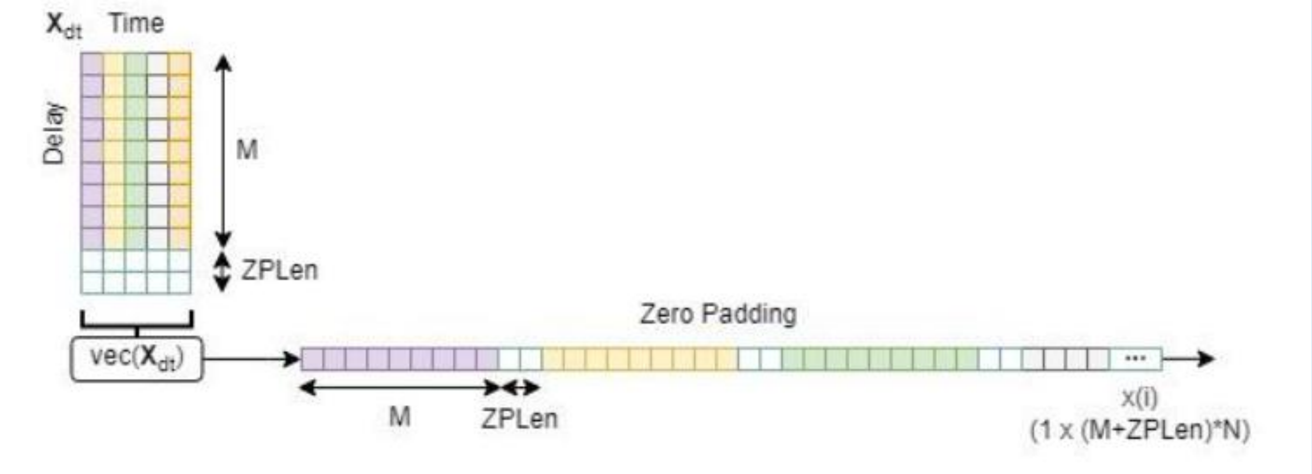


- https://it.mathworks.com/help/comm/ug/otfs-modulation.html

Orthogonal Time Frequency Space (OTFS)

- **Example:** https://it.mathworks.com/help/comm/ug/otfs-modulation.html
- Define X_{dd} the complex *M*x*N* data matrix in the delay/Doppler domain.
- Compute the inverse Zak transform to go to the time domain: $X_{dt} = \frac{1}{M}\,\mathrm{IFFT}\left(X_{dd}^{T}\right)^{T}$ in which T is the transpose operator.
- Then output the discretized time domain samples *x*(*i*) from the vectorized representation of X_{dt}: $x\left(m+nM\right) = \mathrm{vec}\left(X_{dt}\left[n,m\right]\right)$
- Insert a cyclic prefix or a sequence of zeros between OTFS subsymbols or symbols to prevent ISI, similar to how OFDM uses cyclic prefixes. Zero padding (ZP) is an ISI mitigation technique that appends each OTFS subsymbol with zeros of length ZPLen samples.



Orthogonal Time Frequency Space (OTFS)

- Transmit a pilot signal **P**
- Add doppler spread and noise
- **Demodulation**
- After removing the CP, use the Zak transform to demodulate the signal:

$$X_{dd} = M \cdot \mathrm{FFT}\left(X_{dt}^{T}\right)^{T}$$

- A linear minimum mean square error (LMMSE) estimator is an estimation method that minimizes the mean square error between an observation **Y** (the received signal) and the actual value **P** (the known pilot signal), and is given as:

$\mathbf{H} = \dfrac{\mathbf{Y} \cdot \mathbf{P}^{*}}{|\mathbf{P}|^{2} + \sigma_n^{2}}$, being σ_n^2 the noise variance assumed to be known.

- A generic signal model is given as **y**=**Gx**+**n**, where **x** and **y** are the time-domain signals of length MN transmitted into the channel and received from the time-domain channel matrix **G**, respectively. If **G** is estimated, LMMSE can be used to equalize the channel. In matrix form, the LMMSE is given as (to be used as the input of the demodulator):

$$\hat{\mathbf{x}} = \left(\mathbf{G}^{T} \cdot \mathbf{G} + \sigma_n^{2} \mathbf{I}_{MN}\right)^{-1} \mathbf{G}^{T} \mathbf{y}$$

Random Multiple Access

Multiple access A historical perspective

- Fall Joint Computer Conference, 1970.
- Norman Abramson, University of Hawaii
- THE ALOHA SYSTEM—Another alternative for computer communications.

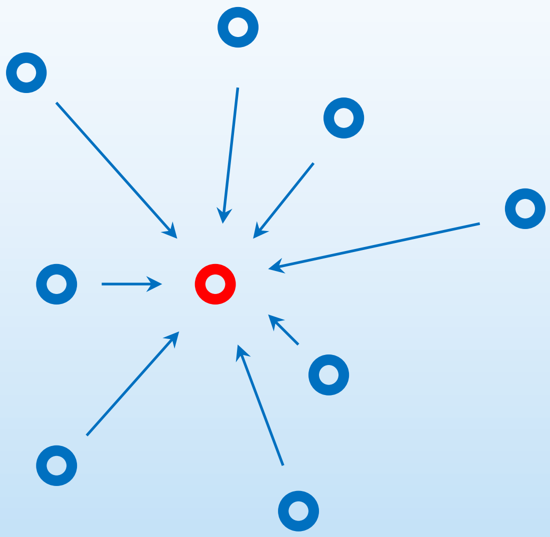
Hawaii


NIIHAU
Puuwai
Kaulakahi Channel
Hanalei
Waialeale
5148
Kapaa
Lihue
Kekaha
KAUAI
Kauai Channel
Haleiwa
Laie
Waialua
Wahiawa
Kaneohe
Kailua
Pearl City
Honolulu
OAHU
Kaiwi Channel
Kalaupapa
MOLOKAI
Maunaloa
Kaunakakai
LANAI
Lanai City
Lahaina
Kahului
Wailuku
Hana
Red Hill
10023
MAUI
KAHOOLAWE
Alenuihaha Channel
PACIFIC OCEAN
Upolu Pt
Hawi
Honokaa
Waimea
Mauna Kea
13796
Hilo
Kailua
Mountain View
Pahoa
Cape Kumukahi
Mauna Loa
13677
Captain Cook
Pahala
HAWAII
Ka Lae

University of Hawaii

- Main campus in Manoa Valley near Honolulu.
- A four year college in Hilo, Hawaii.
- Five two year community colleges on the islands of Oahu, Kauai, Maui and Hawaii.
- An efficient communication network among different buildings.

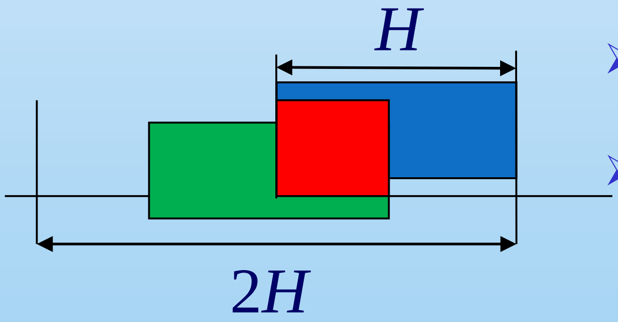
ALOHA System (I)



- *N* uncoordinated computers (users) access independently a common destination (a geostationary satellite).
- Each user (source) may transmit at any time.
- In case of successful reception, the satellite acknowledges the source and delivers the packet to the destination.
- Otherwise the transmission has to be repeated after a random delay (random access).

ALOHA System (II)

- Bursty traffic.
- Uncoordinated stations.
- Long distances.
- Maximum efficiency: 18.4%



- Packet transmission time: *H*.
- Vulnerability window 2*H*.

Multiple access (1)

- Deterministic techniques (Frequency Division, Time Division).
- Polling: a coordinator polls the sources.
- Random access: independent execution of an algorithm with some random parameters.
- Hybrid techniques.

Multiple access (2)

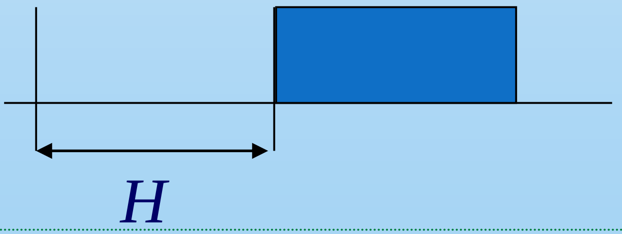
- Design parameters
  - Topology
  - Traffic characteristics (periodic, bursty)
  - Quality of service requirements
    - Delay
    - Efficiency
    - Correct delivery

Slotted ALOHA

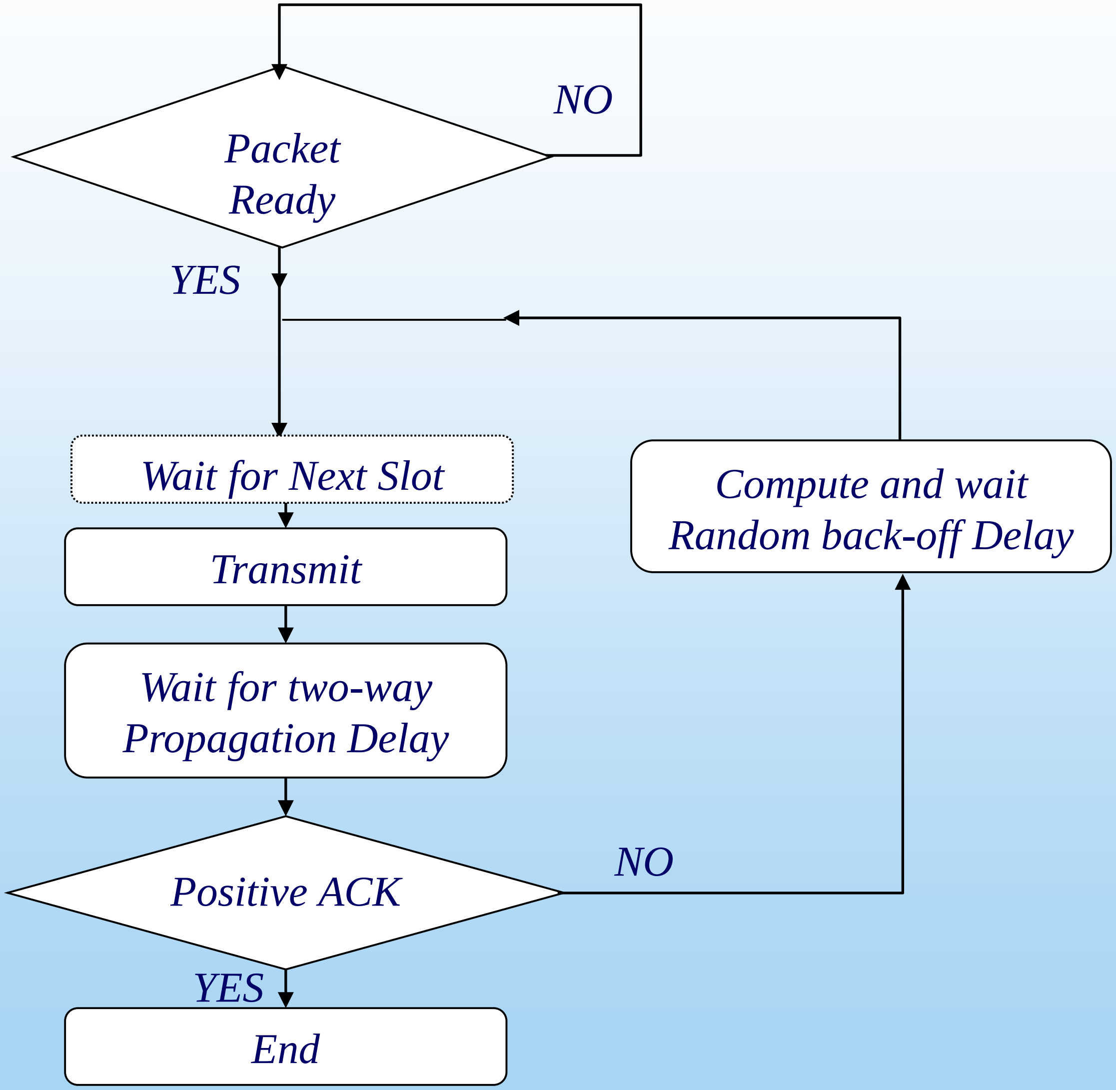
- Time is subdivided into slots.

- One packet occupies one slot.
- May require distance estimation (to ensure slot synchronization at the common receiver).
- Maximum efficiency: 36.8%.

- Vulnerability window: *H*.

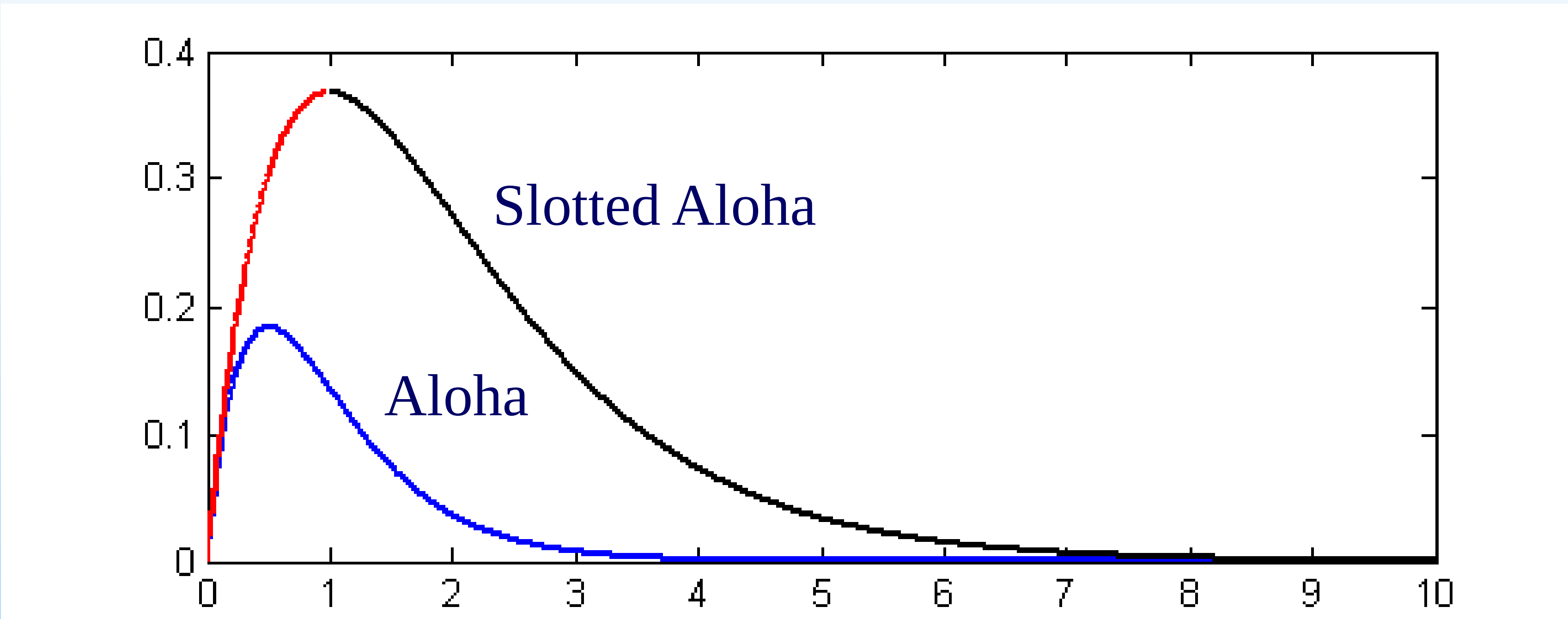


(Slotted) ALOHA System



Efficiency

Successful transmissions per slot



Total transmissions per ‘slot’

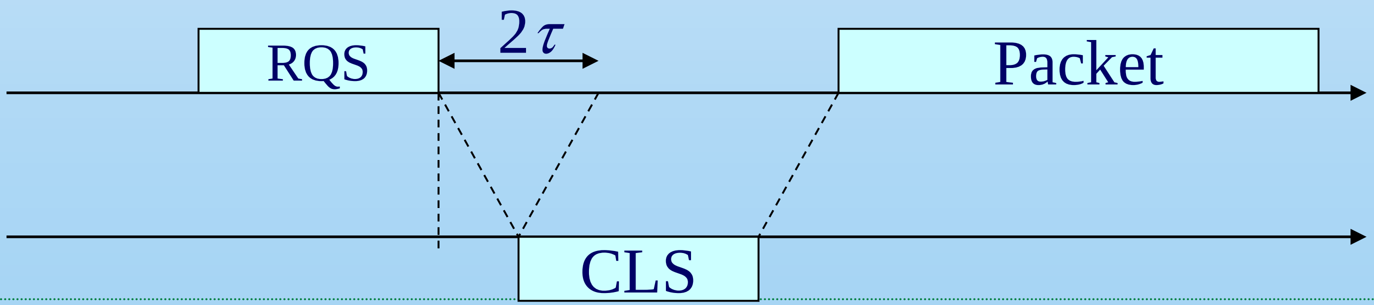
Efficiency

Algorithm	Efficiency
Aloha	1/2e≈0.1839
Slotted Aloha	1/e≈0.3679
Conflict Resolution	0.48775
Berger, Mehravari, and Munson upper bound	0.5254
Tsybakov and Mikhailov upper bound	0.587

Other random access techniques

- *Carrier Sensing Multiple Access* (CSMA): the station checks channel occupancy before transmission: suitable for short distance communication.
  packet transmission time >> propagation delay.

- CSMA + *Collision Avoidance*
  It may use the Request to Send, Clear to Send handshake (in the plot *t* is the propagation delay).



Discussion

- Cellular systems: adopt a mixed TDM, FDM, CDM deterministic scheme, in which resources are assigned by control channels.
  New users enter the system through Slotted Aloha.

- Wireless Local Area Networks (W-LANs): adopt CSMA-CA, given the short propagation delay.

- Sensor Networks: adopt ad-hoc solutions, based on simplicity and low cost requirements.

- Satellite communication: for bursty traffic it adopts Slotted Aloha.

Interference Cancellation

- Modern receivers may implement Interference Cancellation (IC).
- Assume that the received signal is $x=x_1+x_2$.
- Assume that, for example, x_1 may be independently estimated.
- The receiver stores x and evaluates $y=x-x_1=x_2$.
- Now x_2 may be estimated as well.
- At this stage both signals are known.
- If the received signal consists of the combination of more than two signals, the process may be repeated (Successive IC).

Modern multiple access: exploit IC

- Satellite communication: repetition schemes (DVB-RCS2, Digital Video Broadcasting - Return Channel Satellite). It exploits interference cancellation.

Modern multiple access techniques

- Repetition Schemes: they allow one to exploit Interference Cancellation.
- Non Orthogonal Multiple Access (NOMA): they allow one to explain energy diversity. Main characteristics and performance of.
- Further advantages, issues, and opportunities may derive from the joint adoption of NOMA and repetition schemes.

Repetition schemes

- Framed Slotted Aloha

  Time domain subdivided into Random Access Frames (RAFs) consisting of *K* slots of identical duration.

- Repetition scheme

  When the packet is ready, the transmitter waits for a frame boundary.

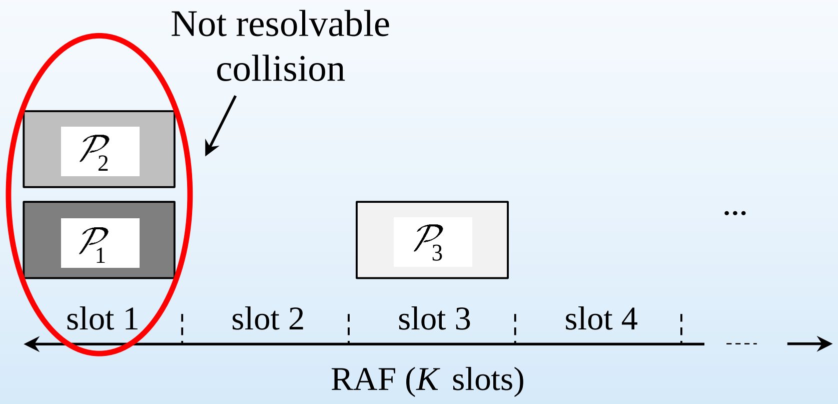
  Within one RAF a packet is transmitted more than once. All packets include a pointer specifying the position of the other replicas in the frame.

Contention Resolution Diversity SA

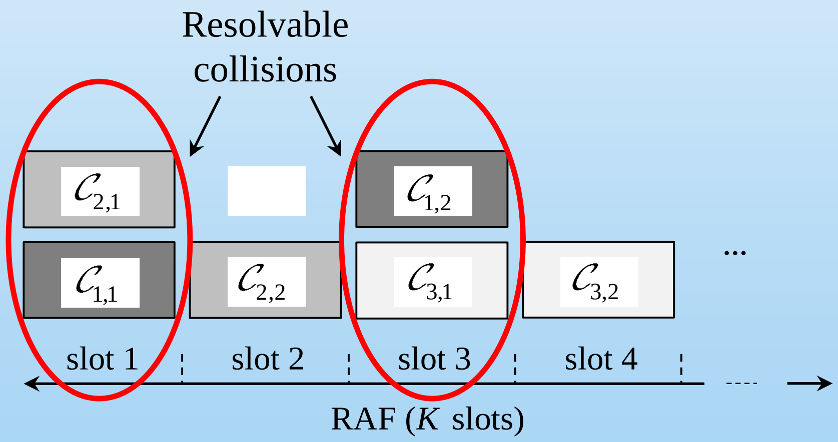
- CRDSA Exploits Interference Cancellation (IC)
  - Two copies of each packet are transmitted to increase the success probability for small loads (which is close to 1 up to a certain threshold: maximum load).
  - IC is used to cancel from the collided slots the interference caused by the packets correctly detected in other slots.
  - The IC decoding process becomes hence iterative, with the iteration one that corresponds to SA with repetition.
  - The maximum efficiency exceeds 0.5 (theoretically evaluated when $K\rightarrow\infty$, through density evolution).

[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. Wireless Commun., vol. 6, no. 4, pp. 1408–1419, Apr. 2007.

Repetition schemes (I)



- Slotted Aloha: Transmission of one copy of each packet.



- Contention Resolution Diversity SA (CRDSA): Transmission of two copies of each packet. Application of Interference Cancellation (IC).

Irregular Repetition SA

- IRSA is an optimized version of CRDSA

  - the number of packet copies transmitted by a node is not fixed, but is selected according to an optimized Probability Mass Function (PMF).
  - IC is used to cancel from the collided slots the interference caused by the packets correctly detected in other slots.
  - Also in IRSA, the IC decoding process becomes hence iterative, with the iteration one that corresponds to SA with repetition and diversity.
  - The efficiency exceeds 0.9.

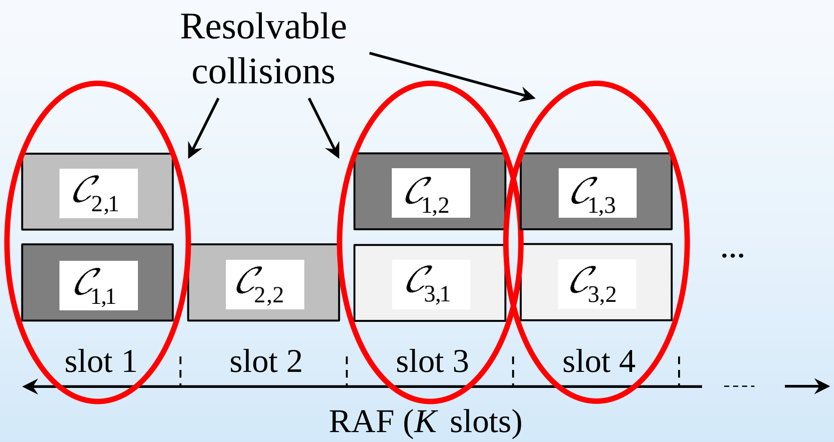
[2] G. Liva, “Graph-based analysis and optimization of contention resolution diversity slotted ALOHA,” IEEE Trans. Commun., vol. 59, no. 2, pp. 477–487, Feb. 2011.

Coded SA

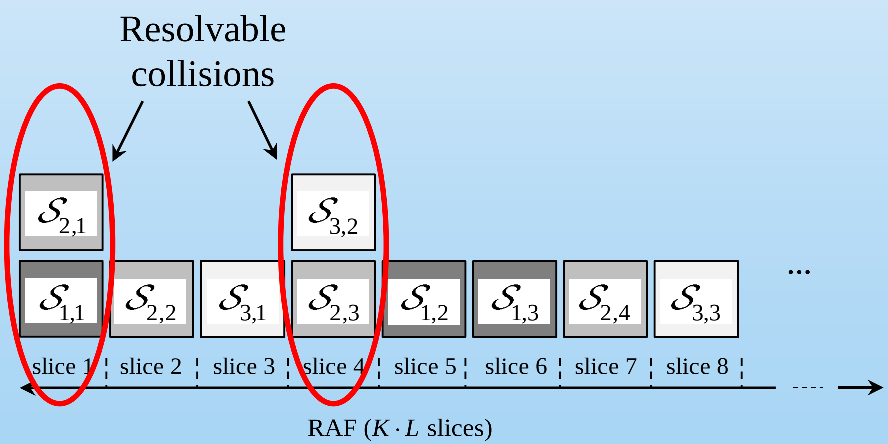
- Packets are encoded instead of simply repeated
  - the packet is split into H data segments that are encoded to produce L segments of the same length.
  - L is selected according to a given PMF (code diversity).
  - Each slot is subdivided into L slices, each having the same duration of the transmission time of a segment. The packets is assumed to be correctly received if at least H clean segments are received (captured).
  - The asymptotic efficiency remains close to 0.9, but CSA presents a higher energy efficiency with respect to IRSA.

[3] E. Paolini, G. Liva, and M. Chiani, “Coded slotted ALOHA: A graph-based method for uncoordinated multiple access,” IEEE Trans. Inf. Theory, vol. 61, no. 12, pp. 6815–6832, Dec. 2015.

Repetition schemes (II)

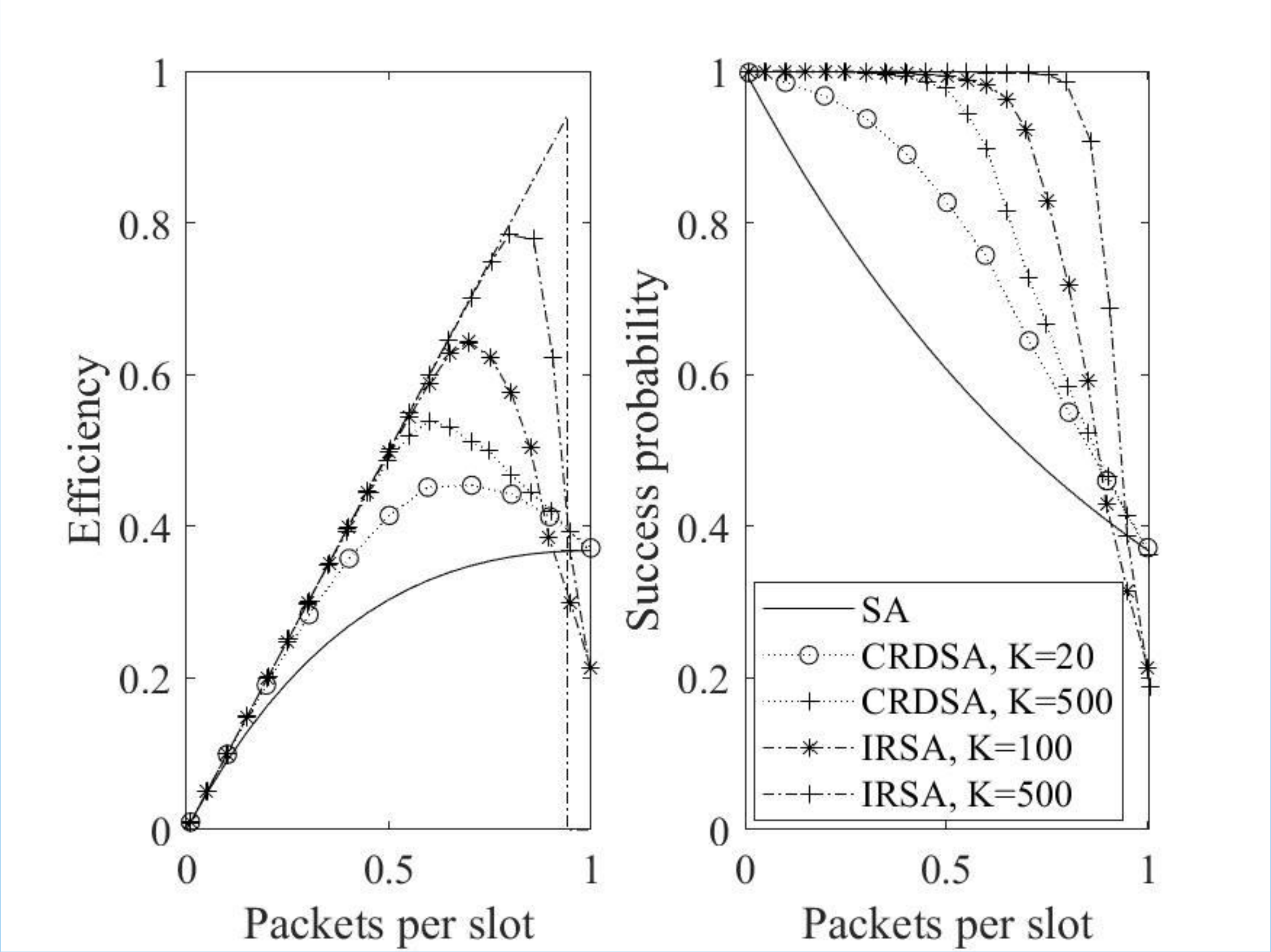


- Irregular Repetition SA (IRSA): Transmission of b_i copies of the i-th packet, where b_i is selected according to a probability mass function (pmf). Application of IC.



- Coded SA (CSA): Splitting of the i-th packet into L segments and encoding at rate R_{c_i} to generate $s_i = L / R_{c_i}$ segments, chosen by a pmf p_{s_i} and transmitted in s_i slices (fractions of a slot). Application of IC.

Efficiency



SA/CRDSA/IRSA

Efficiency and success probability as a function of the load (in packets per slot) for different RAF durations, *K*.

Complexity (repetition and Interference Cancellation), delay (*K*) and diversity (IRSA) allow the performance improvement.

Discussion

- The outlined evolution reveals that, for uncoordinated RA, Slotted Aloha has been gradually improved by adding ever novel features.
  - Packet repetition and IC (CRDSA, IRSA).
  - Slot slicing, packet coding and segmentation (CSA).
- The performance evaluation is based on some simplifying hypotheses.
  - A slot/slice which contains a unique packet/segment is assumed to be successful.
  - A single, collided slot may be assumed to be successful if SINR exceeds a given threshold (segment capture) [4]. Not exploited so far.
  - If not captured, a collided slot/slice is assumed to not provide any information concerning the content of the packets/segments involved in the collision (some capacity is wasted).

[4] E. Khaleghi, C. Adjih, A. Alloum, and P. Muhlethaler, "Near-far effect on coded slotted ALOHA" *2017 IEEE PIMRC*, Montreal, QC, Canada, Oct. 2017.

Multiple access: exploit IC and capture

- Cellular systems: Non Orthogonal Multiple Access (NOMA power domain): it exploits both capture and interference cancellation.

- To be adopted in 5G/6G systems.

Another dimension: power

- Bi-dimensional modulation channel capacity (name S the useful signal power and N the noise plus interference power): $C = \log_2\left(1 + \frac{S}{N}\right)$ bits/symbol.
- Shannon theorem: defined R, the transmission rate (in user bits/channel use), for a reliable transmission: $R < C$.

$$\frac{S}{N} > \alpha = 2^R - 1$$

Capture

- If, among the received packets, there is one which is received with a power that exceeds a given threshold, the packet may be received correctly (it captures the receiver).

$$SNIR = \frac{P_i}{\sum_{j \neq i} P_j + I + N} > \alpha$$

- SNIR: Signal to Noise + Interference ratio.
- *I*: external interference.
- *N*: thermal noise.

NOMA: basic design

- Suppose now that the users may choose among L energy levels (the energy level must be evaluated at the receiver):

$$E_l/N_0 = \alpha_1 (1+\alpha_1)^{l-1}, \quad l=1,\ldots,L \qquad \alpha_1 = m_f \alpha, \quad m_f > 1$$

- If $N \le L$ users independently select different energy levels, the highest energy packet may be decoded correctly, being the correct decoding condition satisfied:

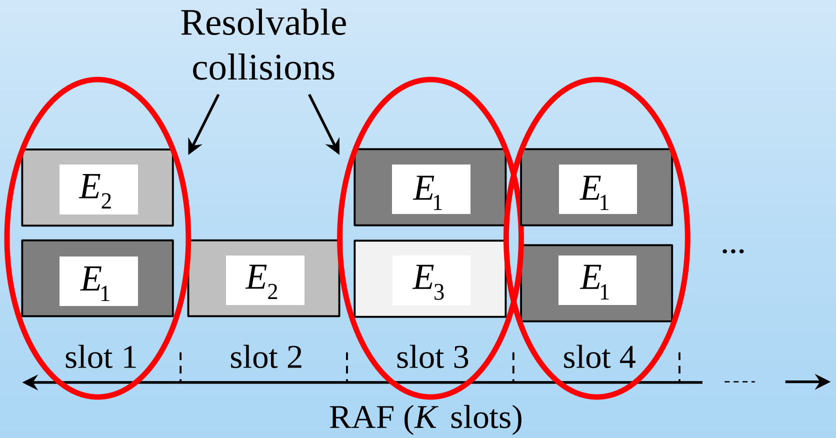
$$\frac{E_l/N_0}{1+\sum_{i=1}^{l-1} E_i/N_0} > \alpha, \quad l=1,\ldots,L$$

- The probability that two users select a different energy level depends on L. The average energy increases with L.

$$E_{\mathrm{AV}}/N_0 = \frac{(1+\alpha_1)^L - 1}{L}$$

(Distributed) NOMA

- Non Orthogonal Multiple Access (in the power domain).
- Operation on a single slot basis (no RAF required).
- Assume a bi-dimensional modulation (two streams).
- Define R the transmission rate in bits/transmission and $a=2^R-1$ the minimum required Signal to Noise plus Interference Ratio (SINR).
- Transmitters may randomly choose among L energy levels which meet the following constraint:



- If all packets select different energy levels, all may be decoded correctly through interference cancellation.
- If Ps is the success probability the performance (*throughput*) may now be expressed by $S=\eta R$ bits / transmission, being $\eta=Ps\,G$ the efficiency, and G the load in packets/slot.

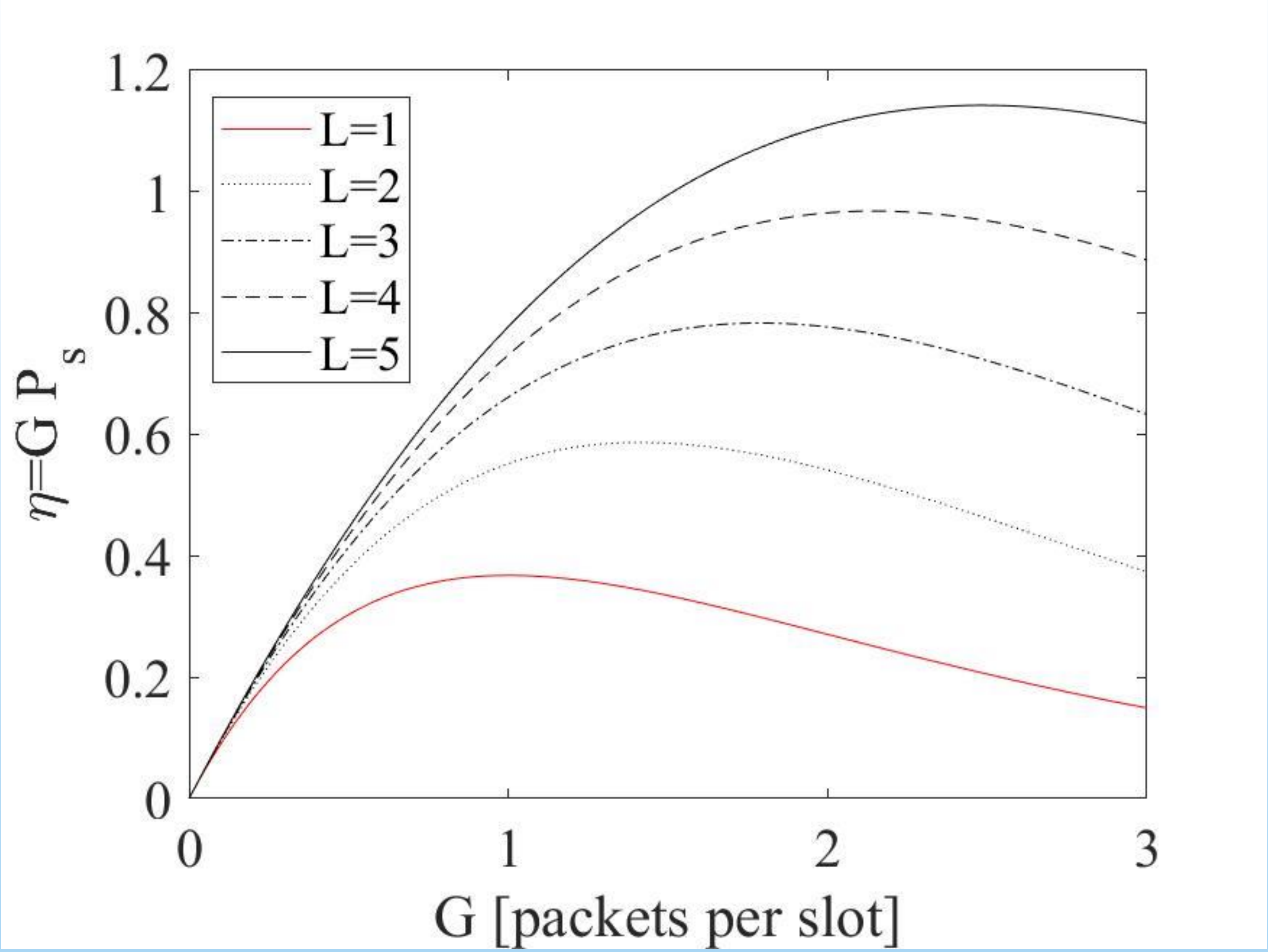
Success Probability

- The relationship among the load G and the success probability P_s, for some values of L, are reported in the following table.

L	Success probability
1	$P_s = e^{-G}$
2	$P_s = e^{-G}\left(1+G/2\right)$
3	$P_s = e^{-G}\left(6+5G+G^2+3e^{G/3}\right)/9$
4	$P_s = e^{-G}\left(32+28G+9G^2+G^3+16e^{G/2}+8\left(G+2\right)e^{G/4}\right)/64$

[5] F. Babich, G. Buttazzoni, F. Vatta, M. Comisso, «Energy-constrained uncoordinated multiple access for next-generation networks». IEEE Open J. Commun. Soc. 2020, 1, 1808–1819

Efficiency



NOMA: robust design

- Consider the air channel model characterized by a two-state semi-Markov chain. One state (the 'Good' state) is characterized by Rice fading and weak shadowing, while the other one (the 'Bad' state) is characterized by severe obstacle attenuation.

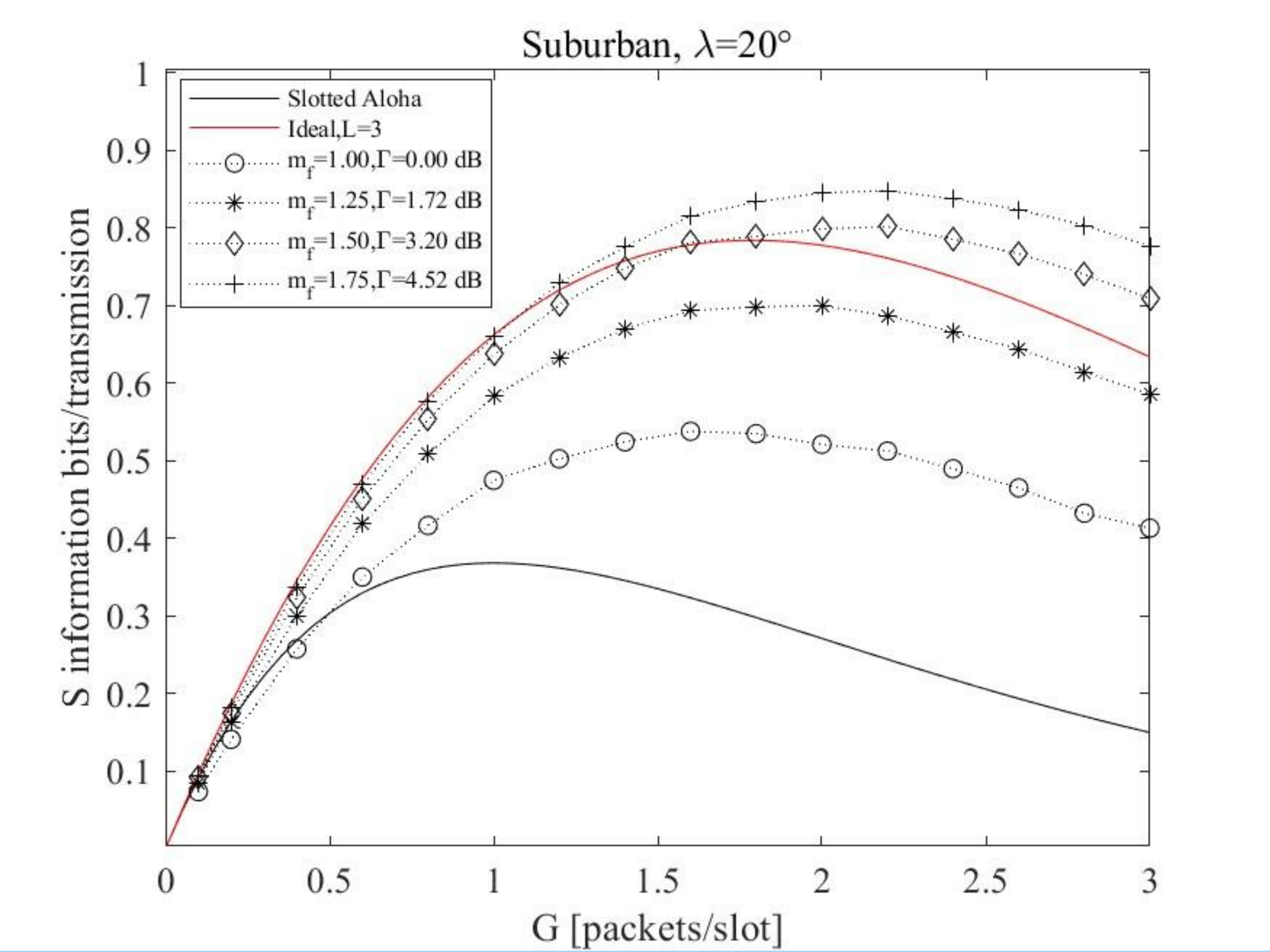
- Assume that the fast variations due to fading cannot be compensated.

- Evaluate the power increment, required, as a function of the scenario and the number of levels, to ensure correct operation.

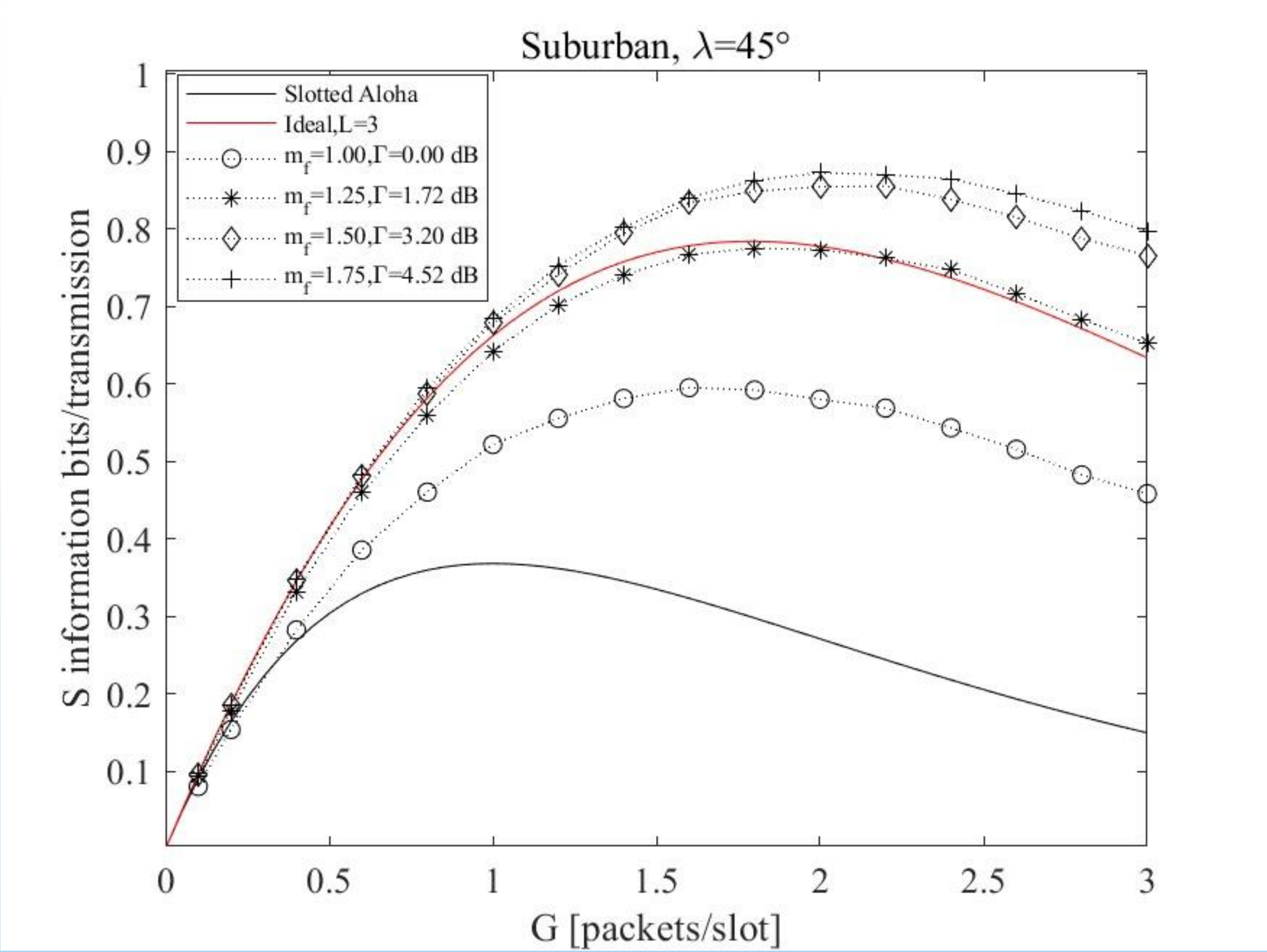
$$\Delta\Gamma = 10\log_{10}\left[\frac{\left(1+m_f\alpha\right)^L - 1}{\left(1+\alpha\right)^L - 1}\right] \text{ dB}$$

- Assume $R = 1$ and $f_c = 3$ GHz and the mobile speed is 2 m/s.

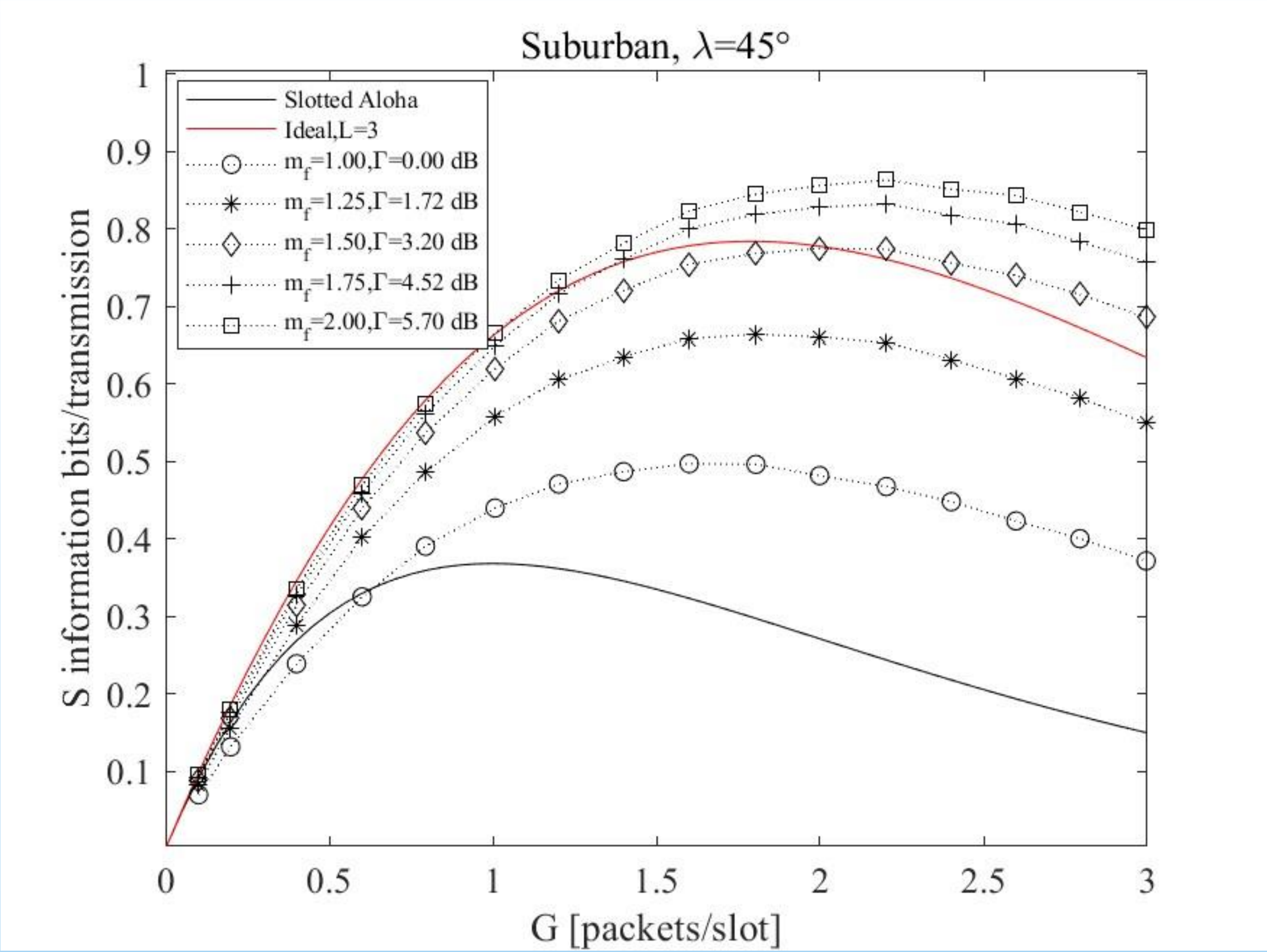
Suburban scenario in the *Good* state



Suburban scenario in the *Good* state



Suburban scenario in the *Bad* state



NOMA: robust design comments

- A limited increment of energy may allow one to approach or even exceed the ideal performance, given the amount of diversity due to fading, significantly outperforming the SA performance.

- For the scenario addressed in the second example, the ’Good’ state requires an increment of approximately 2 dB for facing the average power reduction due to slow fading.

- The further increment due to fast fading in the 'Bad' state is shown in the third example, highlighting that, in the ’Bad’ state, the increment of power required for counterbalancing the fast fading is slightly higher that in the ’Good’ state.

Energy requirements

- NOMA: The limiting E_{AV}/N_0 (ratio between energy per channel use and noise spectral density) values (in dB) as a function of L are reported in the following table (Shannon capacity).

L	R=1	R=5/4	R=3/2	R=7/4
1	0	1.40	2.63	3.74
2	1.77	3.68	5.45	7.13
3	3.68	6.19	8.58	10.92
4	5.75	8.90	11.98	15.02
5	7.93	11.77	15.57	19.35
6	10.22	14.78	19.31	23.83
8	15.04	21.07	27.10	33.12

Maximum throughput

- NOMA: The maximum throughput has a function of the number of levels L, and the rate R.

L	R=1	R=5/4	R=3/2	R=7/4
1	0.37	0.46	0.55	0.64
2	0.59	0.73	0.88	1.03
3	0.78	0.98	1.18	1.37
4	0.97	1.21	1.45	1.69
5	1.14	1.43	1.71	2.00
6	1.31	1.63	1.96	2.29
8	1.60	2.00	2.40	2.80

Limiting the energy (1)

- NOMA: The maximum throughput for $E_{AV}/N_0 < 9$ dB.

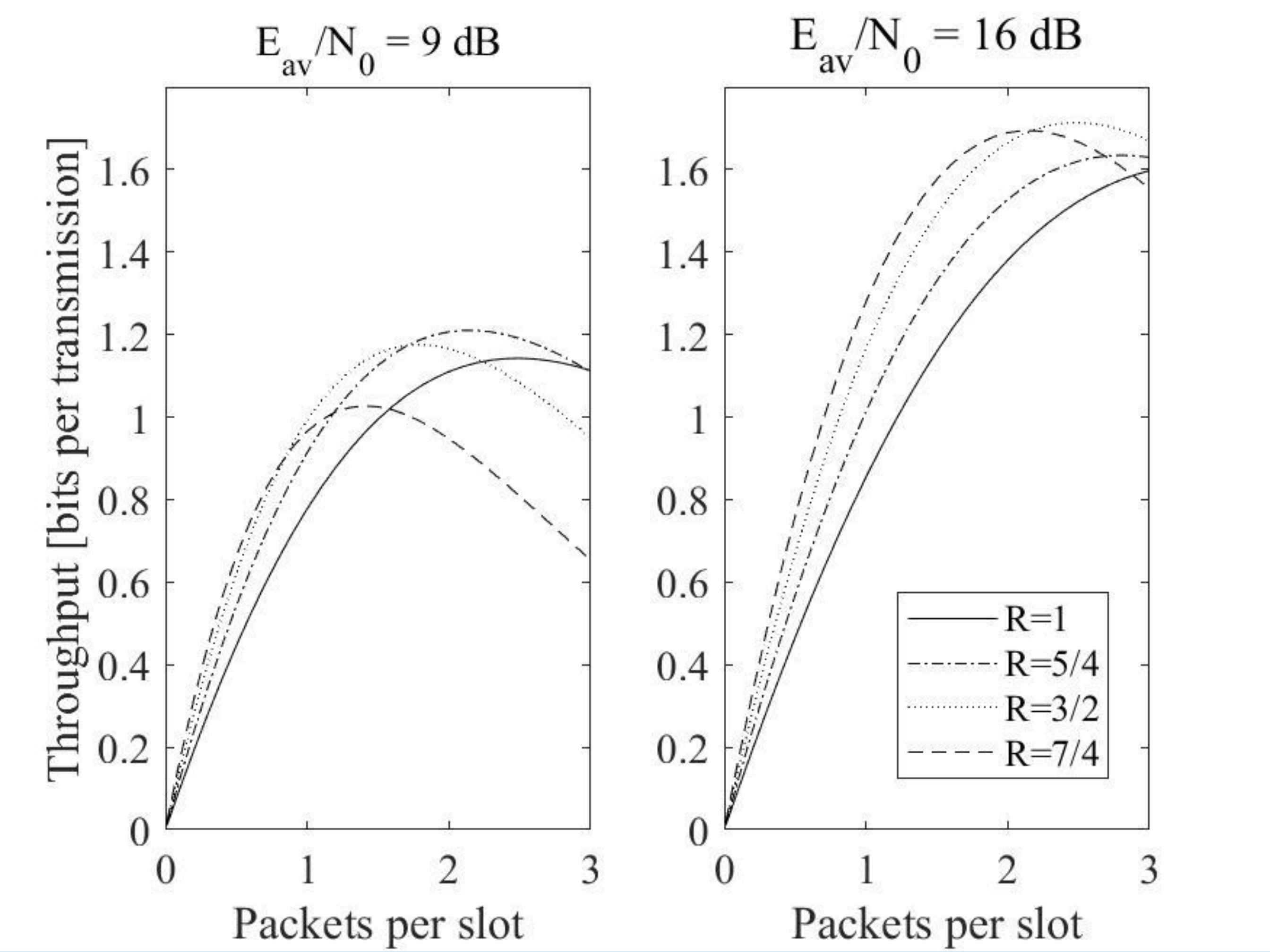
L	R=1	R=5/4	R=3/2	R=7/4
1	0.37	0.46	0.55	0.64
2	0.59	0.73	0.88	1.03
3	0.78	0.98	1.18	1.37
4	0.97	1.21	1.45	1.69
5	1.14	1.43	1.71	2.00
6	1.31	1.63	1.96	2.29
8	1.60	2.00	2.40	2.80

Limiting the energy (2)

- NOMA: The maximum throughput for $E_{AV}/N_0 < 16$ dB.

L	R=1	R=5/4	R=3/2	R=7/4
1	0.37	0.46	0.55	0.64
2	0.59	0.73	0.88	1.03
3	0.78	0.98	1.18	1.37
4	0.97	1.21	1.45	1.69
5	1.14	1.43	1.71	2.00
6	1.31	1.63	1.96	2.29
8	1.60	2.00	2.40	2.80

Throughput=$R\eta$



- NOMA:

throughput as a function of the load (in packets per slot) for different code rates, *R*, and different values of the average signal to noise ratio E_{AV}/N_0

For each curve the maximum *L* value is used.

Discussion

- Assume that the average SNR E_{AV}/N_0 is set
  - There is a trade-off among R and L.
  - The best rate depends on E_{AV}/N_0.
- The actual performance depends on the received power levels
  - Difficult to control in a mobile scenario.
- The actual performance depends on the interference cancellation
  - A residual interference remains.
  - It may counterbalanced by increasing the energy.
- The maximum transmission energy (power) is strictly limited by law.

Imperfect IC (I): robust design

- Define ε the residual amount of interference, after cancellation.
- If all users select different energy levels, the correct decoding condition becomes:

$$\frac{E_l / N_0}{1 + \sum_{i=1}^{l-1} E_i / N_0 + \varepsilon \sum_{i=l+1}^{L} E_i / N_0} > \alpha, \quad l = 1, \ldots, L$$

- The separation among energy levels changes: $\frac{E_l}{E_{l+1}} = \beta = \frac{1+\alpha_1 \varepsilon}{1+\alpha_1}$
- The average energy increases: $E_{\mathrm{AV}} / N_0 = \frac{1}{L} \frac{1-\beta^L}{\beta^L - \varepsilon}$
- being: $\frac{E_L}{N_0} = L \frac{E_{\mathrm{AV}}}{N_0} \frac{1-\beta}{1-\beta^L}$

Imperfect IC (II)

- For $\varepsilon>0$, the maximum number of energy levels is bounded (independently from the available energy).
- If all users select different coding levels, the correct decoding condition implies:

$$L < \frac{\log \varepsilon}{\log\left(2^{-R}(1-\varepsilon)-\varepsilon\right)}$$

- The table summarizes the limiting number of levels.

ε	R=1	R=5/4	R=3/2	R=7/4
0.01	6	5	4	3
0.025	5	4	3	3
0.05	4	3	3	2

Energy requirements

- NOMA: The limiting E_{AV}/N_0 values (in dB) as a function of L are reported in the following table (Shannon capacity), for some e values.

L	ε	R=1	R=5/4	R=3/2	R=7/4
2	.025	1.91	3.93	5.87	7.84
3		4.20	7.28	10.93	17.16
4		7.24	13.49	-	-
5		12.70	-	-	-
2	.05	2.06	4.19	6.34	8.66
3		4.79	8.71	16.25	-
4		9.49	-	-	-

Limiting the energy (3)

- NOMA: The maximum throughput for $E_{AV}/N_0 < 9$ dB

L	ε	R=1	R=5/4	R=3/2	R=7/4
2	.025	0.59	0.73	0.88	1.03
3		0.78	0.98	1.18	1.37
4		0.97	1.21	-	-
5		1.14	-	-	-
2	.05	0.59	0.73	0.88	1.03
3		0.78	0.98	1.18	-
4		0.97	-	-	-

Maximum throughput

- NOMA: The maximum throughput for unbounded energy.

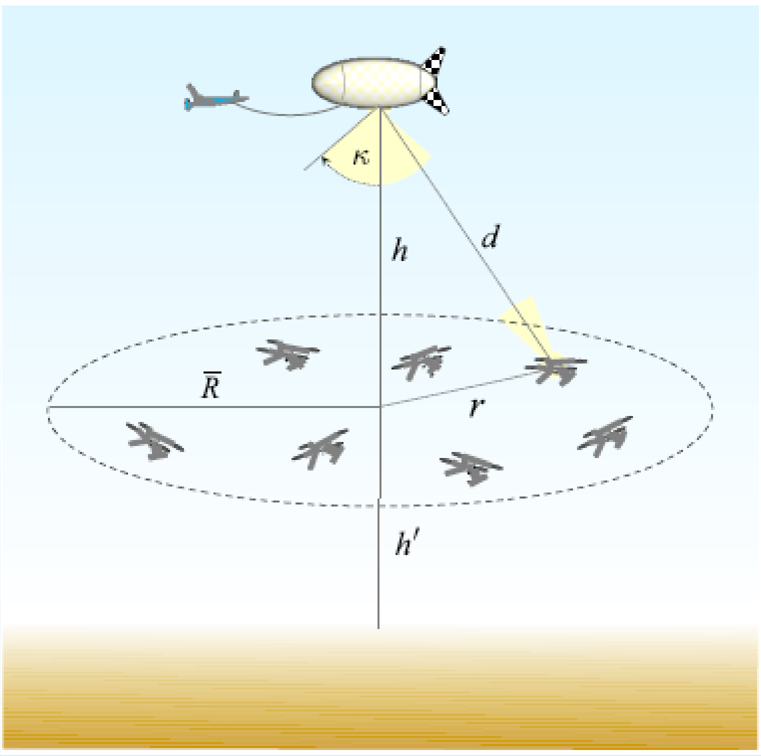
L	ε	R=1	R=5/4	R=3/2	R=7/4
2	.025	0.59	0.73	0.88	1.03
3		0.78	0.98	1.18	1.37
4		0.97	1.21	-	-
5		1.14	-	-	-
2	.05	0.59	0.73	0.88	1.03
3		0.78	0.98	1.18	-
4		0.97	-	-	-

Research in progress

- We are theoretically addressing the estimation of the cdf of the received power and of the coverage probability in PD-NOMA space/aerial networks, developing a semi-analytical approach for calculating the throughput in sub-6 GHz bands.
- Preliminary studies have considered propagation environments characterized by Nakagami fading with random waypoint UAV mobility or scintillation with uniformly located satellites.
- More advanced investigations have been focused on a UAVs-HAP uplink scenario, further including in the model airframe shadowing, multi-lobe antenna patterns, pointing errors, and different code-modulation schemes.
- Results have shown that, in a realistic propagation context, a lower order modulation characterized by a higher coverage probability may be preferable to a higher order modulation characterized by a lower coverage probability.

M. Comisso, F. Babich, et al., "Power-Domain Non-Orthogonal Multiple Access for Distributed Non-Terrestrial Networks: A Semi-Analytical Throughput Estimation", 12th IEEE International Workshop on Metrology for Aerospace (MetroAroSpace 2025)

Research in progress



Joint techniques

- Consider the joint adoption of CRDSA/IRSA and NOMA assuming an energy constraint.
  - Define E[M] the average number of segments.
  - Basic design: the average normalized energy is now given by

$$E_{\mathrm{AV}}/N_0 = \mathrm{E}\left[M\right]\frac{\left(1+\alpha_1\right)^L - 1}{L}$$

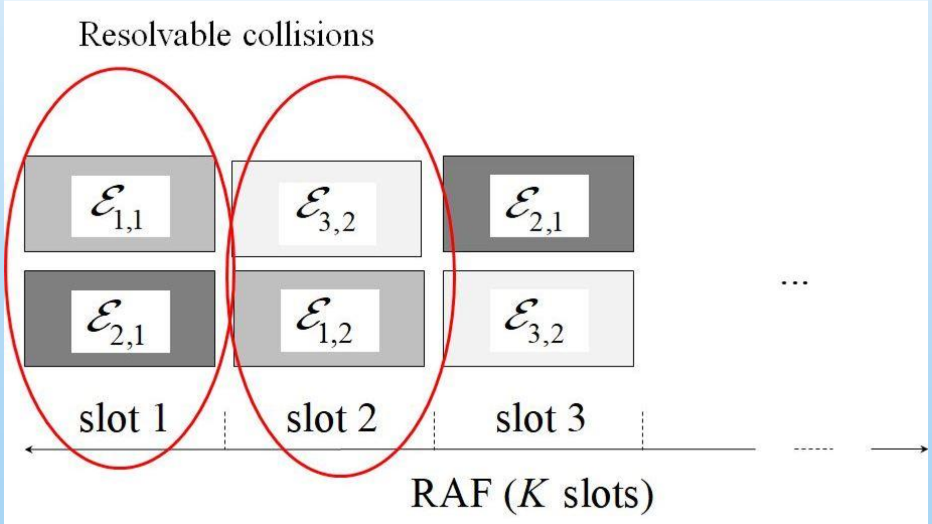
  - M = 2 segments are used by CRDSA.
  - For IRSA the Probability Mass Functions are determined in [6] for $M_{\max}$=8 and in [7] for $M_{\max}$=3.

[6] X. Shao, Z. Sun, M. Yang, S. Gu, and Q. Guo, "NOMA-based irregular repetition slotted ALOHA for satellite networks," IEEE Commun. Lett., vol. 23, no. 4, pp. 624–627, Apr. 2019.

[7] F. Babich, G. Buttazzoni, F. Vatta, M. Comisso, "Energy-Constrained Design of Joint NOMA-Diversity Schemes with Imperfect Interference Cancellation". Sensors, 2021.

Joint techniques

- In the figure $\mathcal{E}_{i,j}$ represents the energy selected by the user *i* for its *j*-th attempt. User 1 chooses the energy level 1 for its first attempt, and the energy level 2 for the second one. We have a collision in the first and in the second slot, since both users choose the same energy level. In the third slot, instead, the transmitters choose different energy levels, thus, according to the NOMA rules, their packets can be successfully decoded by starting from the higher energy one.



In this way, the contribution of users 1 and 3 may be (partly) removed from the other slots, hence allowing the correct detection of packet 2 as well by assuming that the remaining interference is within the design threshold.

Maximum load

- The table summarizes the achievable performance (the maximum load, *G*, in packets per slot, determined through Density Evolution, which allows the full packet delivery, which may be approached for a sufficiently long frame and perfect IC).

L	NOMA/ CRDSA	NOMA/ IRSA-3	NOMA/ IRSA-8	NOMA
1	0.55	0.82	0.94	**0.37**
2	1.00	1.29	1.43	0.59
3	1.46	1.69	1.86	0.78
4	1.86	2.07	2.27	0.97
5	2.23	2.43	2.65	1.14
6	2.57	2.77	3.02	1.31

Energy requirements

- Assuming R=7/4, the minimum E_{AV}/N_0 values (in dB) as a function of L are reported in the following table.

L	**NOMA**		**NOMA/ CRDSA**		**NOMA/ IRSA-8**	
	E[M]	E_{AV}/N_0	E[M]	E_{AV}/N_0	E[M]	E_{AV}/N_0
1	1	3.74	2	6.75	3.60	9.3
2	1	7.12	2	10.13	3.23	12.22
3	1	10.92	2	13.93	3.02	15.72
4	1	15.02	2	18.03	3.00	19.78
5	1	19.34	2	22.35	2.98	24.08

Limiting performance

E_{av}/N_0 [dB]

L/R	1	5/4	3/2	7/4
1	0.00	1.39	2.62	3.74
2	1.76	3.67	5.44	7.12
3	3.68	6.18	8.58	10.92
4	5.74	8.89	11.97	15.02
5	7.92	11.77	15.56	19.34

L/R	1	5/4	3/2	7/4
1	4.50	5.90	7.12	8.24
2	5.90	7.81	9.58	11.26
3	7.63	10.13	12.53	14.86
4	9.58	12.73	15.81	18.85
5	11.69	15.54	19.33	23.11

NOMA

NOMA/IRSA-3

S_{max}

L/R	1	5/4	3/2	7/4
1	0.37	0.46	0.55	0.64
2	0.59	0.73	0.88	1.03
3	0.78	0.98	1.18	1.37
4	0.97	1.21	1.45	1.69
5	1.14	1.43	1.71	2.00

L/R	1	5/4	3/2	7/4
1	0.82	1.03	1.23	1.44
2	1.29	1.61	1.94	2.26
3	1.69	2.11	2.54	2.96
4	2.07	2.59	3.11	3.62
5	2.43	3.04	3.65	4.25

Discussion

- Joint NOMA/repetition techniques allow one to achieve both a high sustainable load and full packet delivery.
- An imperfect interference cancellation may severely affect the performance, because it reduces the maximum number of utilizable energy levels, and it increments the requested energy significantly (joint techniques are energy demanding).
- The limiting performance may be approached by using long frames: complexity and delay.
- The delay may be significantly reduced by adopting a frame asynchronous approach.

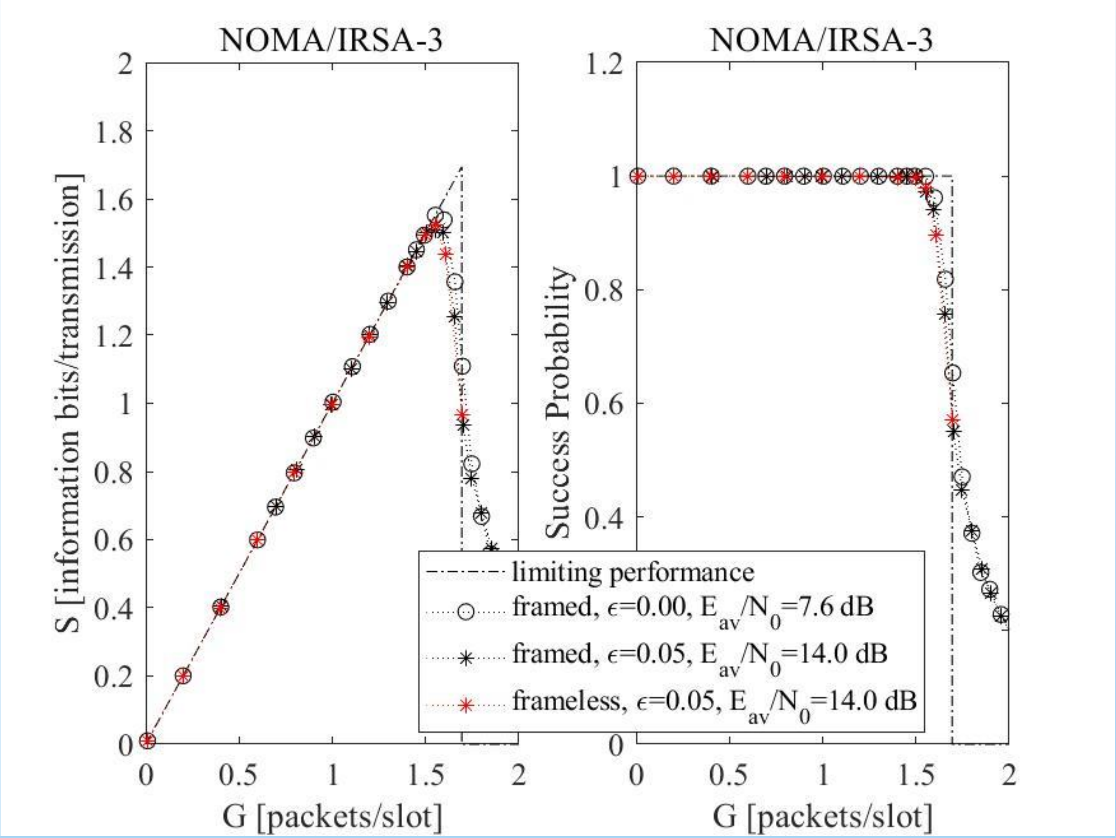
[8] Yu-Chih Huang, Shin-Lin Shieh, Yu-Pin Hsu, and Hao-Ping Cheng, "Iterative Collision Resolution for Slotted ALOHA with NOMA for Heterogeneous Devices," IEEE Trans. on. Comm., vol. 69, no. 5, pp. 2948 - 2961, May. 2021

Frame asynchronous approach

- The transmitter synchronizes with the slot sequence only (as in Slotted Aloha) and transmits its replicas in a randomly chosen set of slots (starting from the first one) within a maximum interval said ‘private frame’.
- The receiver examines an interval consisting of more than one ‘private frame’ (the complexity moves from the transmitter to the receiver).
- It may be shown the maximum performance is approached when the receiver examines up to 5 ‘private frames’.
- The performance of the frame asynchronous scheme approach the framed one, with a ‘private frame’ that is 1/5.
- The delay is significantly reduced.

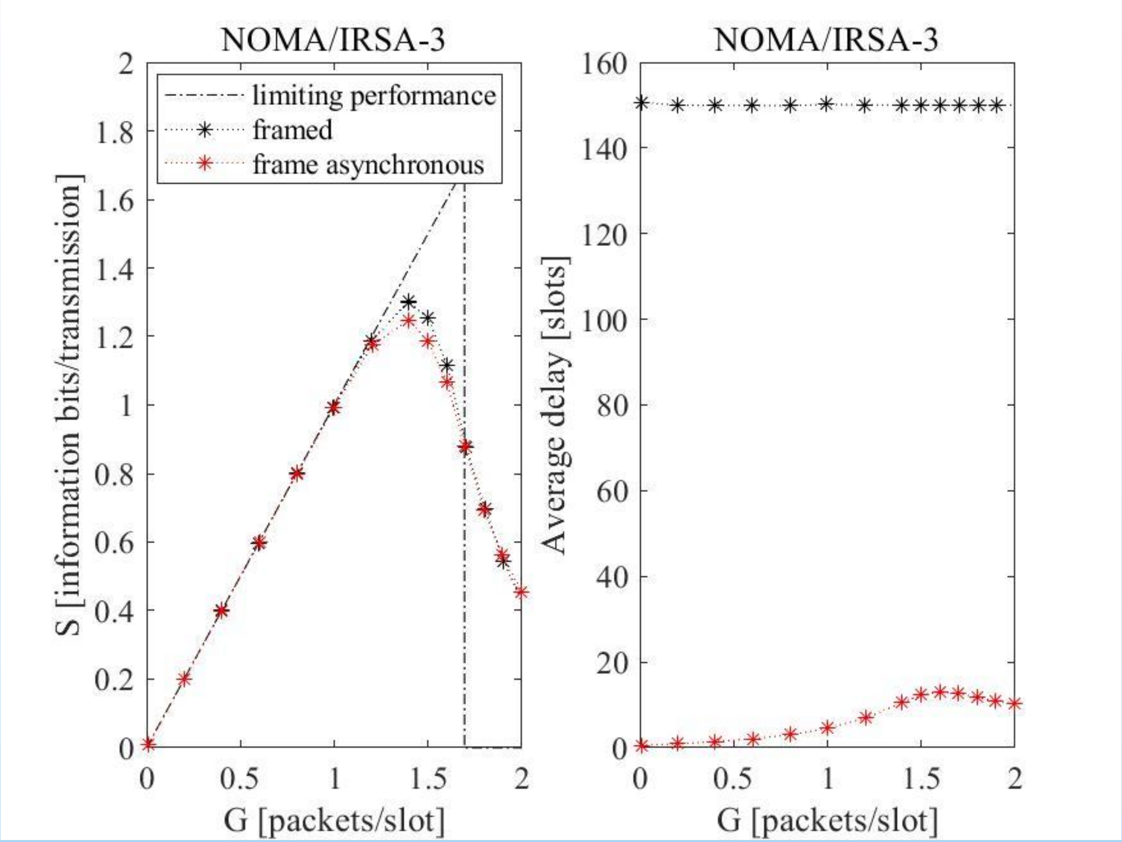
Frame asynchronous performance

- Performance comparison *K*=1000 (framed) and ‘private frame’=200 (frameless), *L*=3, and *R*=1 information bits per symbol: NOMA/IRSA-3.



Frame asynchronous performance

- Performance comparison K=100 (framed) and ‘private frame’=20 (frameless), L=3, and R=1 information bits per symbol: NOMA/IRSA-3.



Research in progress

- We are investigating the use of blind source separation (BSS) as a replacement for, or in conjunction with, coded random access (CRA) in diversity ALOHA for massive machine-type communications.
- These networks employ a Massive MIMO base station to receive data from multiple users.
- A slotted ALOHA framework is considered, where users transmit synchronously in distinct time slots.
- By applying BSS, we extract user payloads without relying on power differences, code assignments, or orthogonal preambles, but instead leverage the spatial diversity captured by the multiple antennas.
- BSS is most effective when combined with CRA, as it enhances conflict resolution among users.

M. Godeas, A. Carini1, F. Babich, L. Valentini, and E. Paolini, “Code Random Access and Blind Source Separation for Massive Machine-Type Communications” at the 33rd European Signal Processing Conference (EUSIPCO 2025).