EUSPACE 2020

Multiple access techniques for heterogeneous 5G/6G-Satellite Networks

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A heterogeneous 5G-Satellite Network

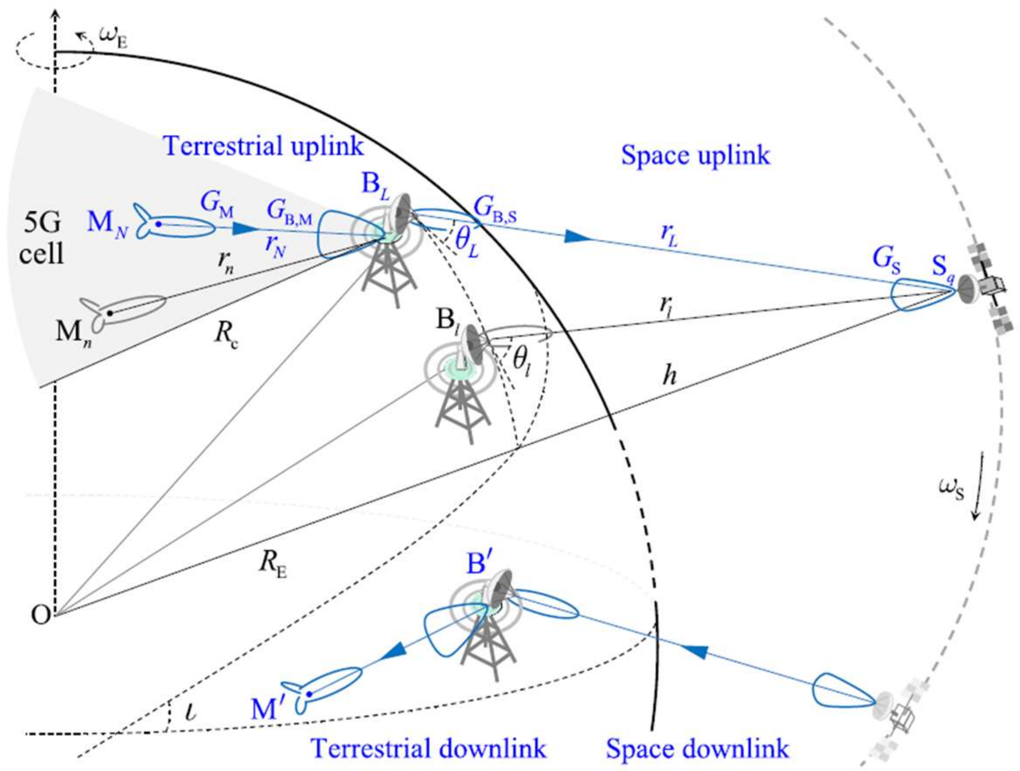


Fig. 1. End-to-end communication scenario.

F. Babich, M. Comisso, A. Cuttin, M. Marchese, and F. Patrone, "Nanosatellite-5G Integration in the Millimeter Wave Domain: A Full Top-Down Approach", *IEEE Transactions on Mobile Computing*, Vol. 19, N. 2, February 2020, pp. 390-404.

1G to 6G (I)

- 1G: first generation (AMP, TACS, NMT)

  Analog communication. Speech traffic only.

- 2G: second generation (GSM)

  Digital communication. Circuit switching. Frequency/Time Division Multiple Access. Short Message Service (SMS), Circuit Switched Data (CSD) to transmit data at speeds up to 14.4 kbit/s.

- 2.5 – 2.75 (GPRS, EDGE)

  GPRS: Packet switching.

  EDGE: better radio interface, for data speed up to 384 kbit/s.

1G to 6G (II)

- 3G: third generation (UMTS)

  Code Division Multiple Access (CDMA).

  Multimedia traffic.

  IP address assigned for handling a data exchange.

- 4G: fourth generation (LTE)

  Orthogonal Frequency Division Multiple Access (OFDMA).

  Evolved Packet System, for real time and data traffic. IP address assigned when the terminal is switched on. Connection within 100 ms.

1G to 6G (III)

- 5G: fifth generation

  Low latency (Ultra Reliable Low Latency Communication).

  Edge computing. Local Cloud.

  Dense antenna deployment: Beamforming.

  New frequencies: millimeter wave communication.

  Service flexibility: Virtualization. Network function. Slicing.

  Internet of Things (massive Machine Type Communication).

- 6G: sixth generation

  Further developments, based on Artificial Intelligence and Quantum Communication.

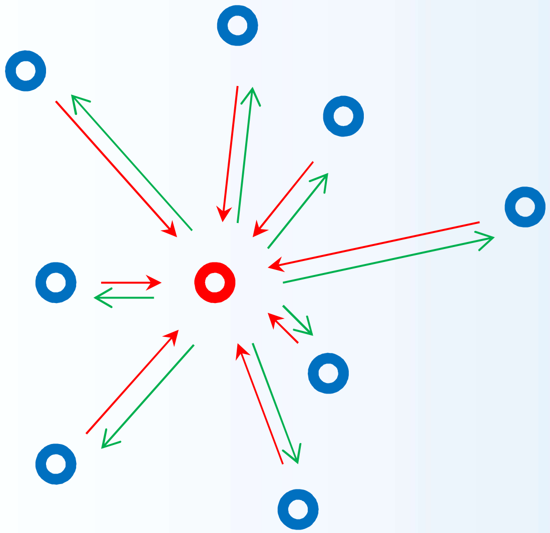
Multiple access: Outline

- Multiple access: what is it?
- A historical perspective
- Random multiple access
- Modern multiple access techniques
- Discussion

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.

A historical perspective

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

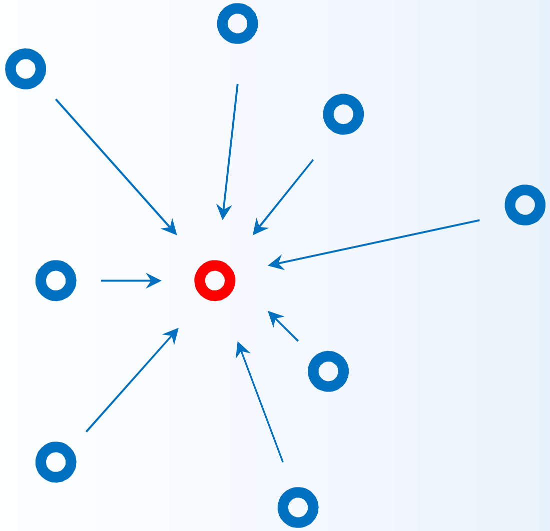
Hawaii

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 Kumukah
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.

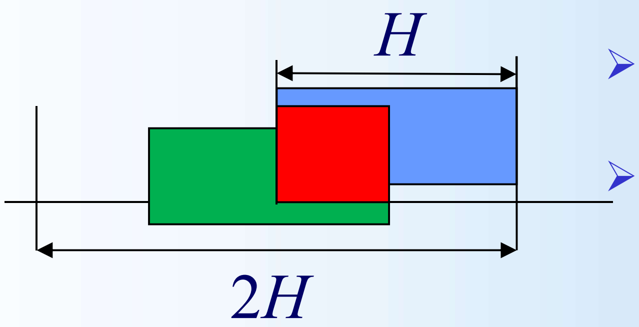
ALOHA System (I)



- 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%



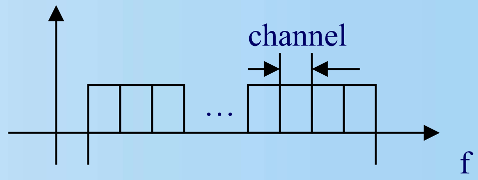
- Packet transmission time: *H*.
- Vulnerability window 2*H*.

Multiple access (1)

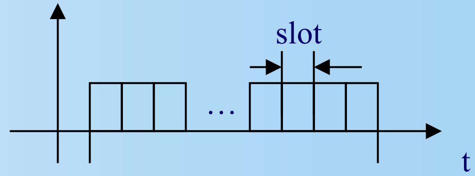
- Deterministic techniques (Frequency Division, Time Division).
- Polling: a coordinator polls the sources.
- Random access: independent execution of an algorithm with some random parameters.
- Hybrid techniques.

Multiple access (2)

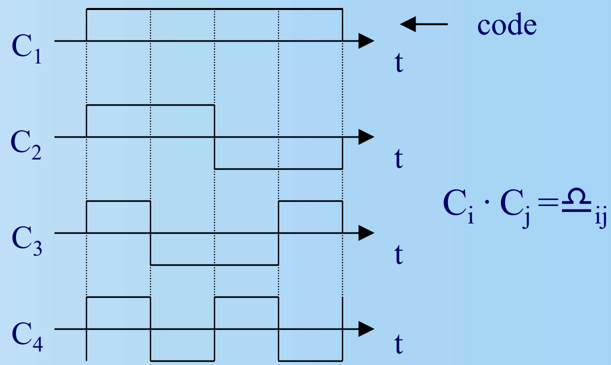
- Frequency Division Multiplexing (FDM) / Frequency Division Multiple Access (FDMA): different transmitters use different frequencies (1G, 2G, 4G).



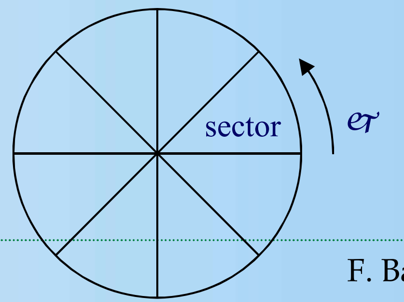
- Time Division Multiplexing (TDM) / Time Division Multiple Access (TDMA): different users transmit at different times (2G, 4G).



- 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).

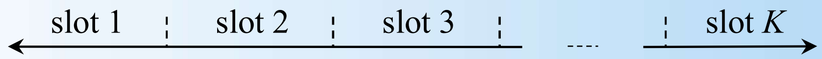


Multiple access (3)

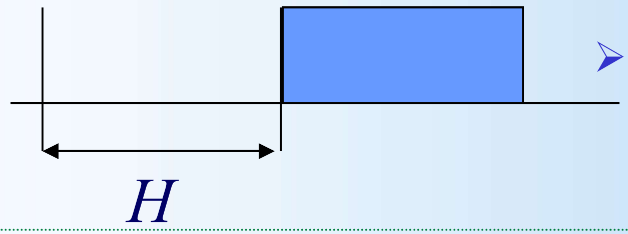
- Design parameters
  - Topology
  - Traffic characteristics (periodic, bursty)
  - Quality of service requirements
    - Delay
    - Efficiency
    - Correct delivery

Slotted ALOHA

- Time is subdivided into slots.

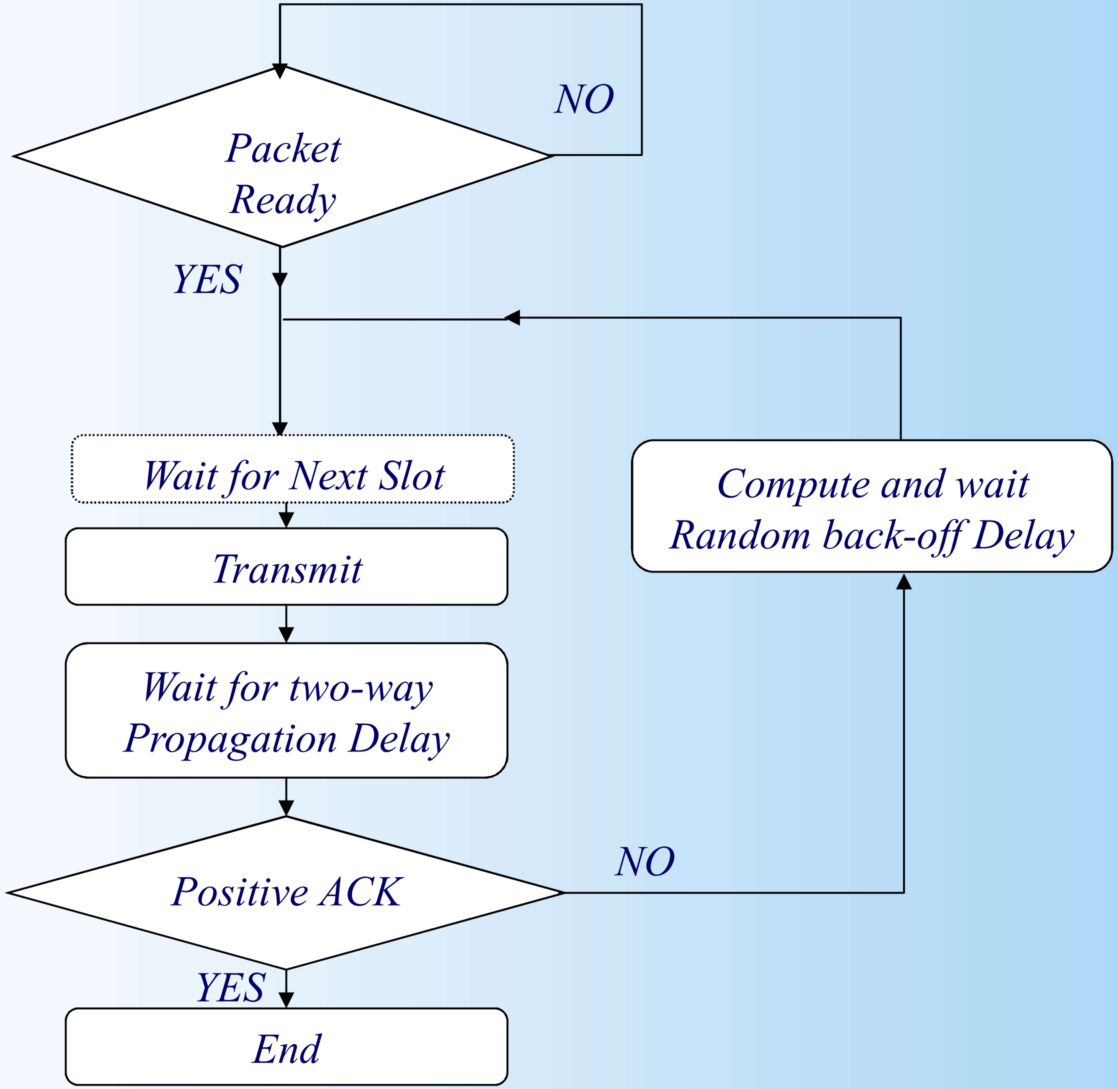


- One packet occupies one slot.
- May require distance estimation (to ensure slot synchronization at the common receiver.
- Maximum efficiency: 36.8%.



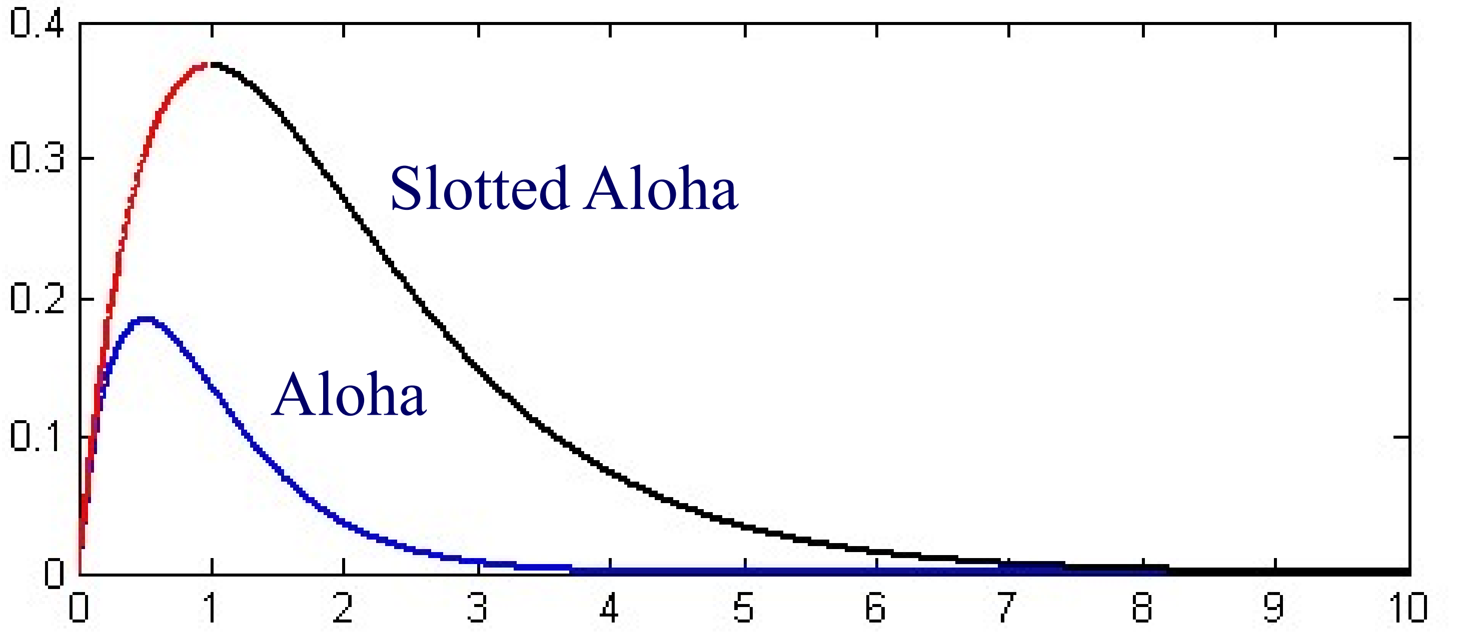
- Vulnerability window: *H*.

(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

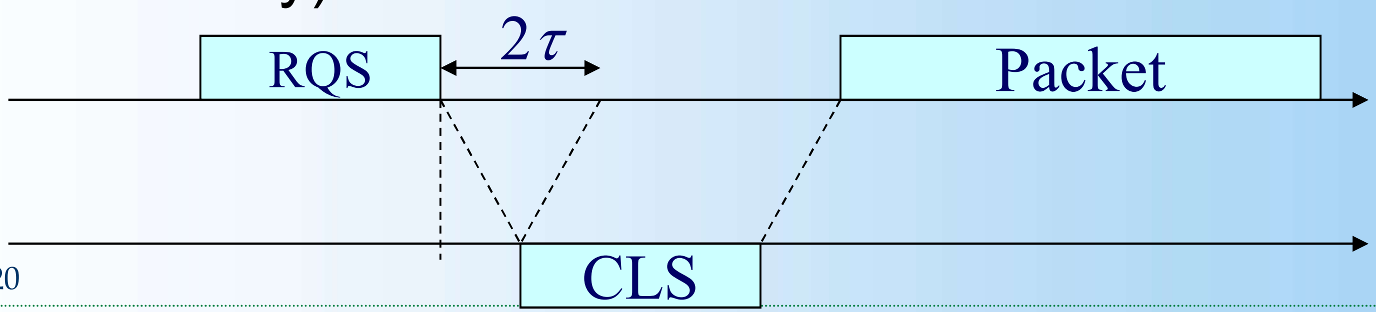
Other random access techniques

- *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 τ 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.

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).

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

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

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 $y=x-x_1=x_2$.
- 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

- Cellular systems: Non Orthogonal Multiple Access (NOMA): it exploits both capture and interference cancellation.
- To be adopted in 5G systems.

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

Repetition schemes

- Framed Slotted Aloha

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

- Repetition scheme

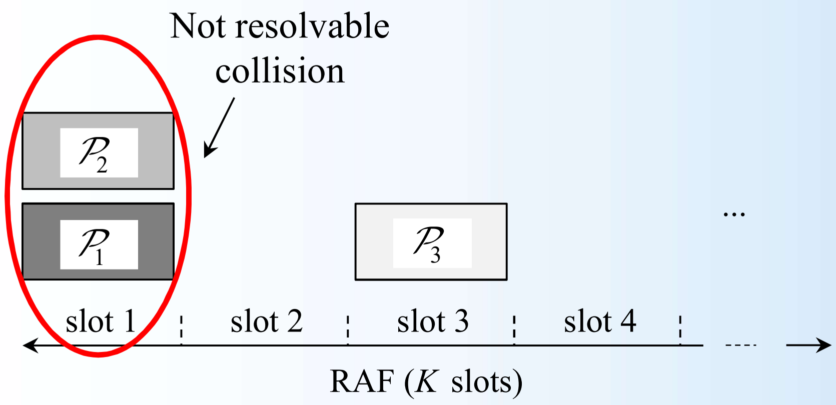
  Within one RAF a packet is transmitted more than once.

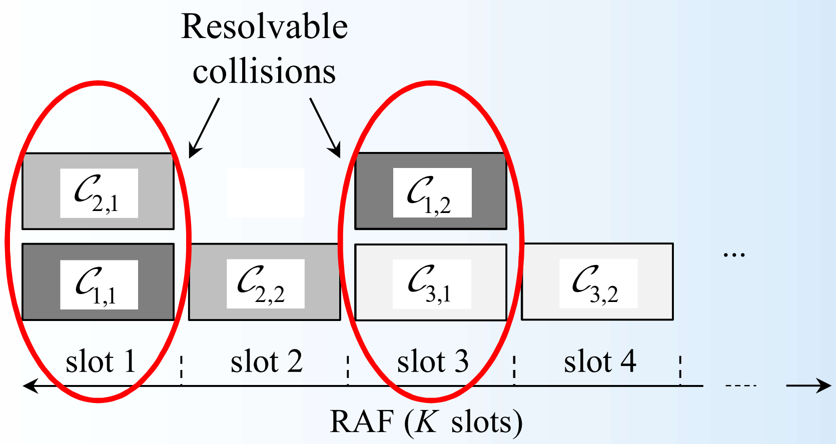
Contention Resolution Diversity SA

- Exploits Interference Cancellation (IC)
  - Two copies of each packet are transmitted to increase the success probability for small loads.
  - 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.

[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)





- SA: 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.

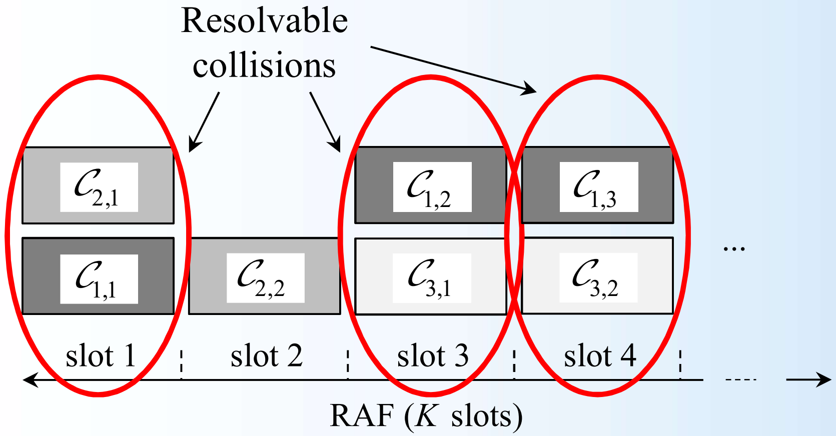
[2] G. Liva, "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA," IEEE Trans. Commun., vol. 59, no. 2, pp. 477–487, Feb. 2011.

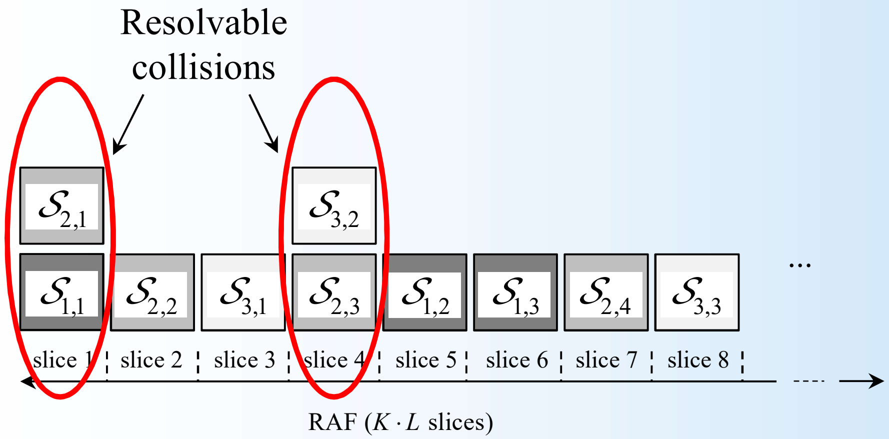
Coded SA

- 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.
  - 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.

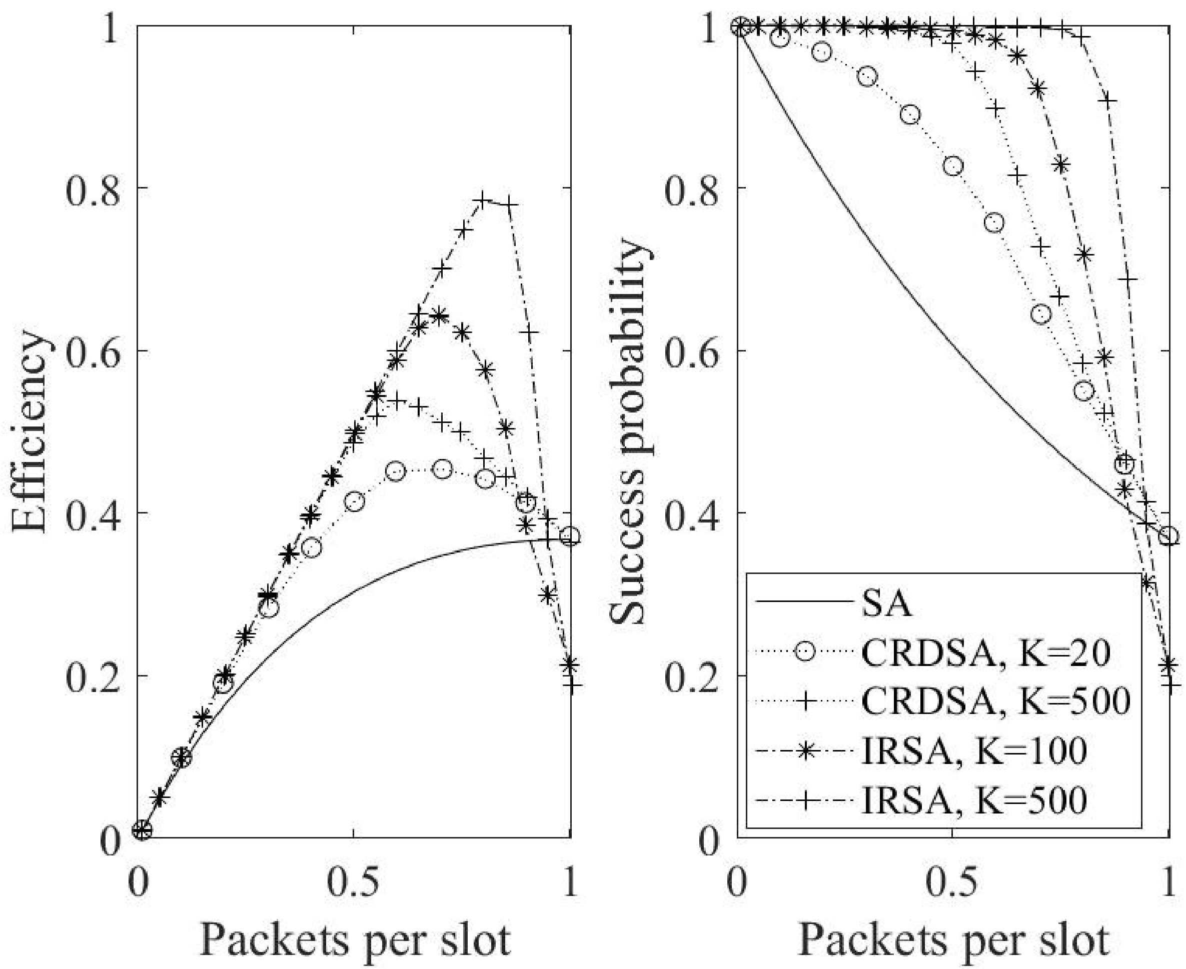
Repetition schemes (II)





- 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.

Throughput



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.

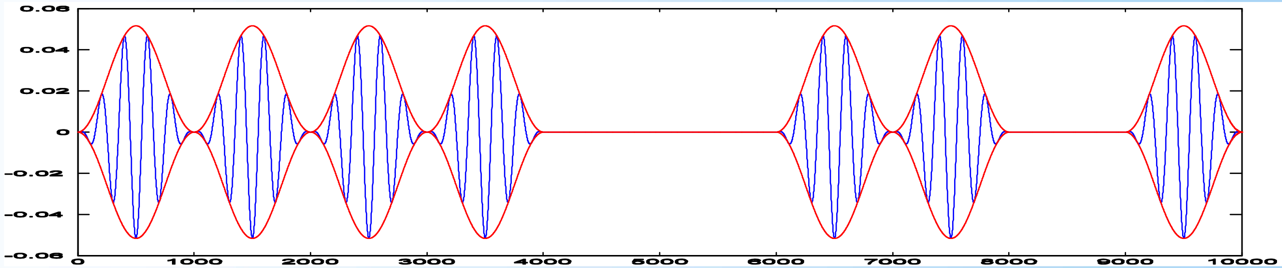
Discussion

- The outlined evolution reveals that, for uncoordinated RA, Slotted Aloha has been gradually improved by adding ever novel features.
  - Packet repetition and IC.
  - Slot slicing, packet coding and segmentation.
- 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].
  - 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.
  - However, if coding is adopted, a collided segment might provide a residual information, which may be associated with that provided by other segments of the same packet to possibly recovery the packet itself (packet capture).

[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.

Another dimension: power

- Digital communication: the transmitted signal may be seen as a succession of waveforms (symbols), chosen within a finite number of possibilities $M=2^b$.



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

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

Discussion

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Exploiting the power domain

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

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

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

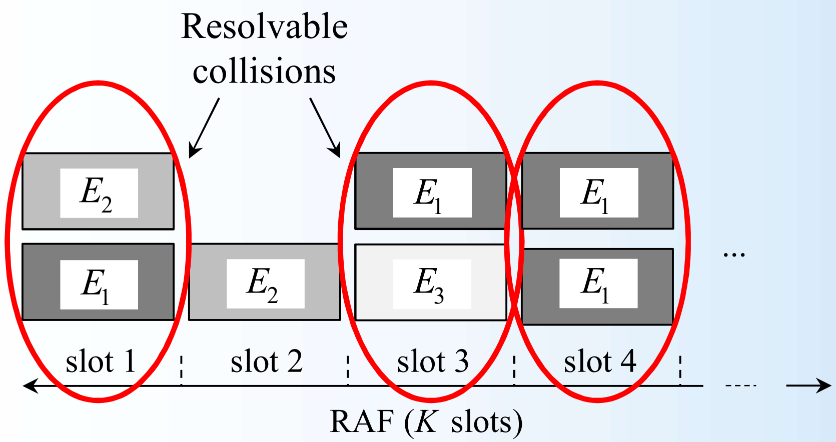
$$\frac{E_l/N_0}{1+\sum_{i=1}^{l-1} E_i/N_0} > \alpha, \quad l = 1,\dots,L$$

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

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

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 $\alpha=2^R-1$ the minimum required Signal to Noise plus Interference Ratio (SINR).
- Packets may randomly choose among *L* energy levels which meet the following constraints:



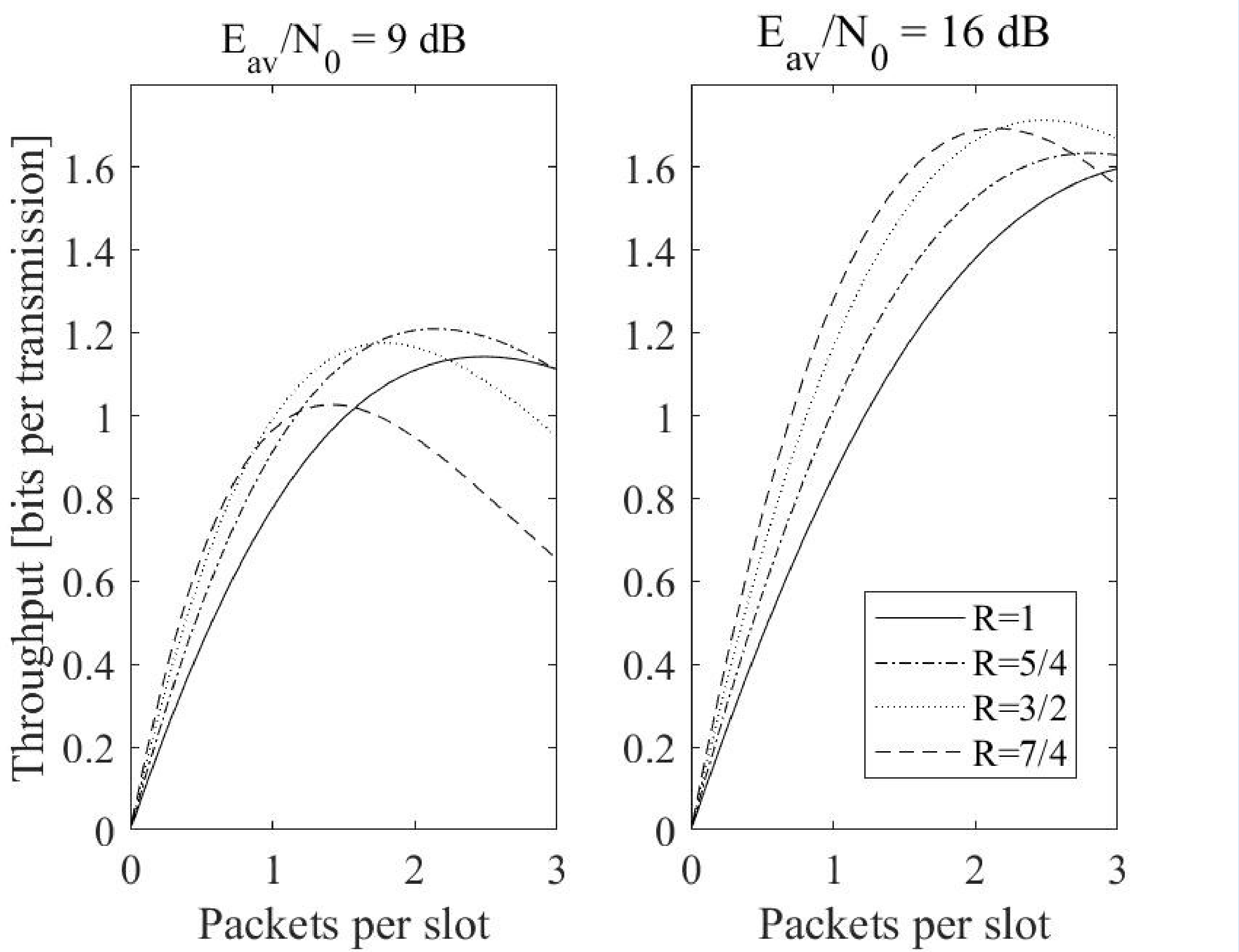
- If all packets select different energy levels, all may be decoded correctly through interference cancellation.
- If *Ps* is the success probability the performance (*throughput*) may now be expressed by $S=\eta$ *R* bits / transmission, being $\eta=Ps\, G$ the efficiency.

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).

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

Throughput



- 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

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 margin m).
- The maximum transmission energy (power) is strictly limited by law.

6G: Under investigation

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

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

  - $M = 2$ segments are used by CRDSA.
  - For IRSA an example of *M* values is determined in [5].

[5] 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.

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		CRDSA		IRSA	
	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

Discussion

- The outlined evolution reveals that, for uncoordinated RA, Slotted Aloha has been gradually improved by adding ever novel features.
  - Packet repetition and IC.
  - Slot slicing, packet coding and segmentation.
- The performance evaluation is based on some simplifying hypotheses.
  - A slot/slice which contains a unique packet/segment is assumed to be successful.
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  - However, if coding is adopted, a collided segment might provide a residual information, which may be associated with that provided by other segments of the same packet to possibly recovery the packet itself (packet capture).

Capture evaluation

Success probability may be carried out at the first round of capture, that is, when IC has not been even applied to the RAF.

For CRDSA and IRSA, three capture models may be adopted

Erasure channel → The *i*-th packet is successfully decoded if at least one segment meets the SINR requirements. The other segments are neglected and do not contribute to the successful decoding.

Chase combining → The *i*-th packet is successfully decoded if the sum of the SINRs meets the SINR requirements. All segments contribute to the successful decoding, but their position must be determined before decoding (self decodable pointer).

Code combining → The *i*-th packet is successfully decoded if the average rate is larger or equal to *R,* that is (a pointer is also required):

$$\psi_{\mathrm{e}} = \frac{1}{L}\sum_{l=1}^{L} \psi_l \geq R$$

<u>rate</u> (in bits/s·Hz) <u>achievable</u> by the *l*-th segment of the *i*-th packet.

Comments

- Assuming suitable energy constraints, CRDSA/NOMA and IRSA/NOMA schemes benefit from an increased availability of energy and from a longer frame duration (that is, from an increased delay).

- CRDSA and IRSA allow a significant increment of the success probability at low to moderate loads, making retransmissions unnecessary.

- More advanced reception criteria, able to exploit the content of all the received replicas or segments, should be used to better exploit repetitions and different energy levels.

- However, a suitable self-decodable pointer should be added to each segment to allow Chase or code combining.

Conclusions

- Repetition schemes represent suitable access schemes for the satellite segment.
- NOMA may represent a suitable multiplexing scheme for the terrestrial segment (cellular system).
- Mobility issues (imperfect power control) may prevent its adoptions for uncoordinated multiple access.
- Joint repetition/NOMA schemes may offer interesting performance improvements, if efficient (and complex) decoding schemes are adopted (the feasibility of which is under investigation).
- However, a suitable self-decodable pointer should be added to each segment to allow Chase or code combining.

Further readings

- F. Babich and M. Comisso, "Segmented Framed Slotted Aloha (SFSA) with Capture and Interference Cancellation", in VTC2018-Spring, Porto, Portugal, pp. 1-5.
- F. Babich and M. Comisso, “Impact of segmentation and capture on slotted Aloha systems exploiting interference cancellation,” IEEE Trans. Veh. Technol., vol. 68, no. 3, pp. 3613–3627, Mar. 2019.
- F. Babich and M. Comisso, “Impact of header on coded slotted Aloha with capture,” IEEE ISCC 2019.
- F. Babich and M. Comisso, “Energy-Constrained NOMA with Packet Diversity for Slotted Aloha Systems”, IEEE MedComNet 2020.