a prospect in wireless research: embracing heterogeneous connectivity

Petar Popovski
Professor
Head of Connectivity
Aalborg University
Denmark

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outline

- the future connectivity landscape
- redefining the way to deal with heterogeneity
- how model enrichment drives innovation
- slicing of wireless resources
- outlook and final remarks

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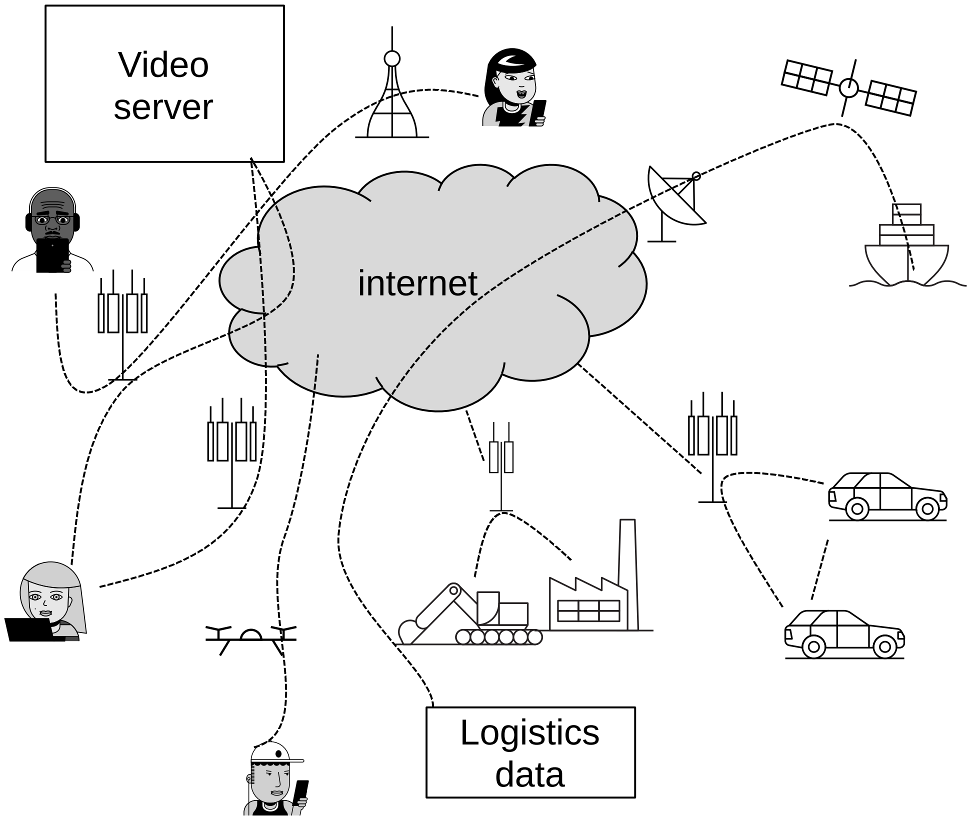
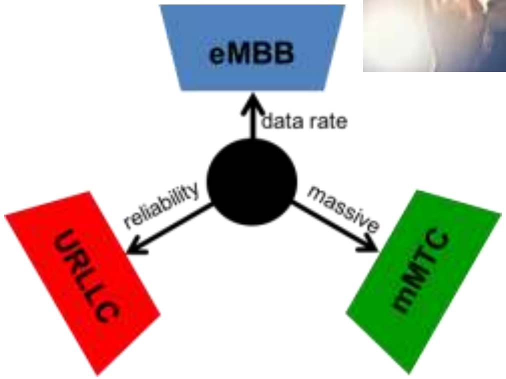
the complex connectivity ecosystem



5G segmentation to deal with complexity

enhanced Mobile Broadband

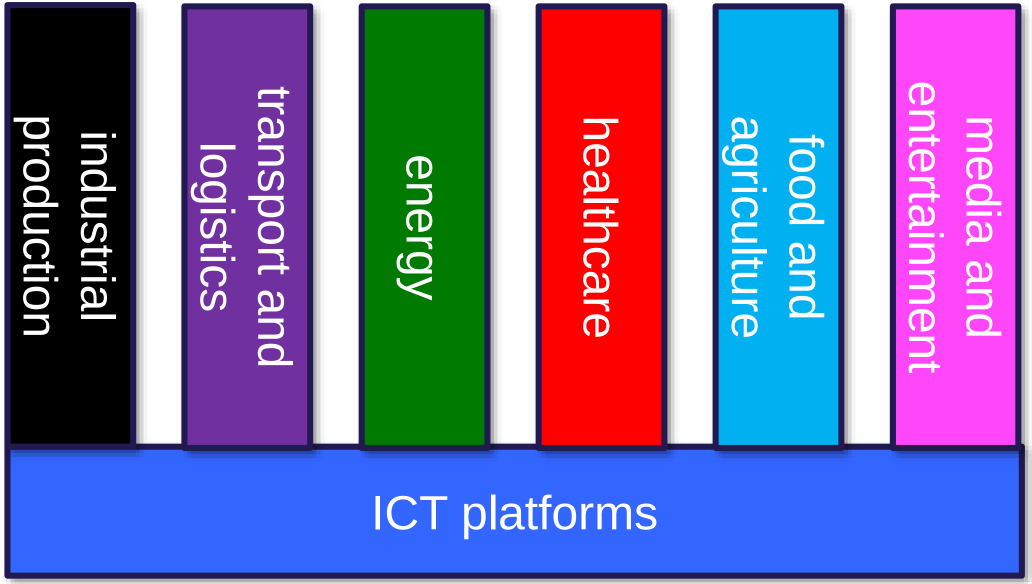


Ultra-Reliable
Low Latency
Communication

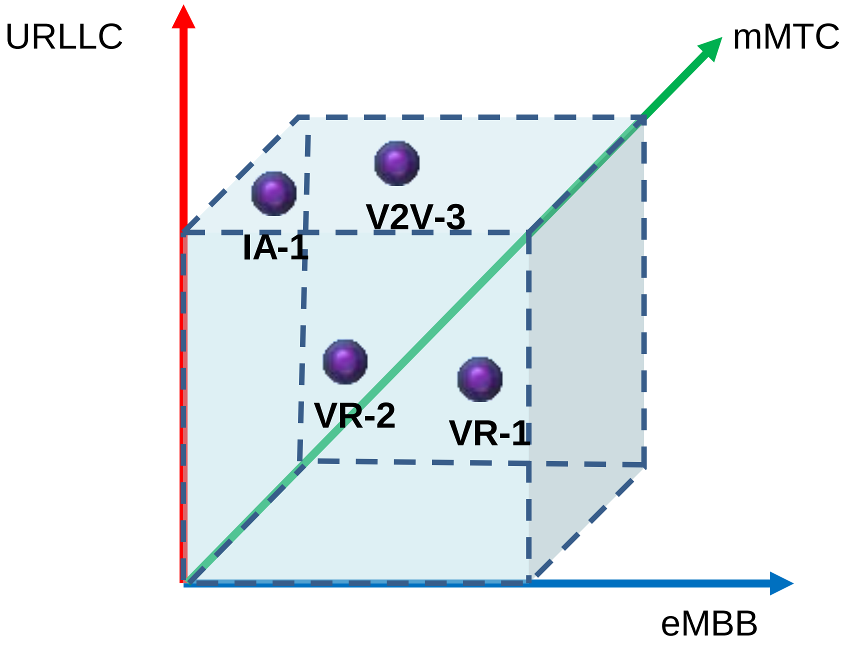
massive
Machine Type Communication

the platform approach of 5G

- roughly 2/3 of 5G is dedicated to IoT communication
- connecting the **vertical** sectors



the space of connectivity services



IA: Industrial Automation

VR: Virtual Reality

V2V: Vehicle-to-Vehicle

5G offers flexible composition of services

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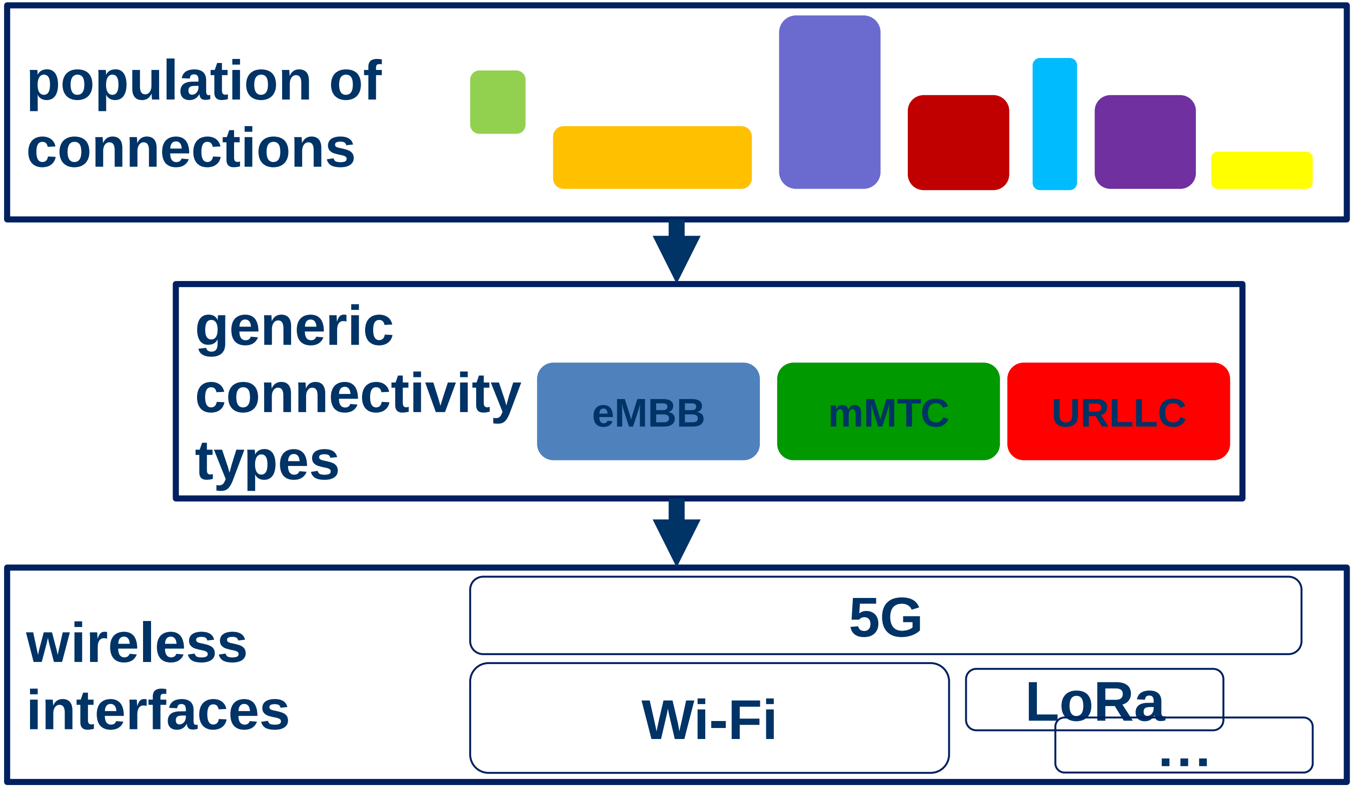
is this the ultimate connectivity framework?

it would appear that we have reached the limits of what it is possible to achieve with computer technology, although one should be careful with such statements, as they tend to sound pretty silly in 5 years.

von Neumann   Feynman   Ulam

Picture from: https://around.com/glimpse-of-the-past/

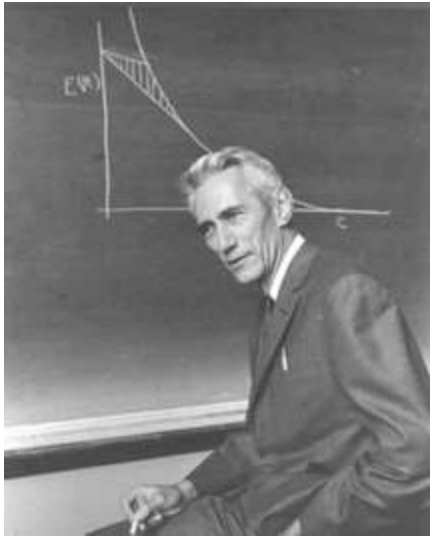
relation to other wireless interfaces



the weak marriage of ultra-reliability and low latency

the 5G community has opted
to couple the ultra-reliability and low latency into URLLC

- error rate of 10^{-5} under the proverbial 1 ms



information theory guarantees
perfect reliability!

- ...provided that the sender **knows** the channel statistics to be able to select the data **rate** to be below the channel **capacity**
- at the price of an **infinite latency**

URLLC vs. URC (ultra-reliable communication)

early METIS proposal [1]:

- URC over a long term: latency >10 ms
- URC over a short term: latency ≤ 10 ms

we still need a latency constraint for high reliability,
but the value of 1 ms will need to be revisited

[1] P. Popovski, “Ultra-reliable communication in 5G wireless systems,” in *1st International Conference on 5G for Ubiquitous Connectivity*, Nov. 2014, pp. 146–151.

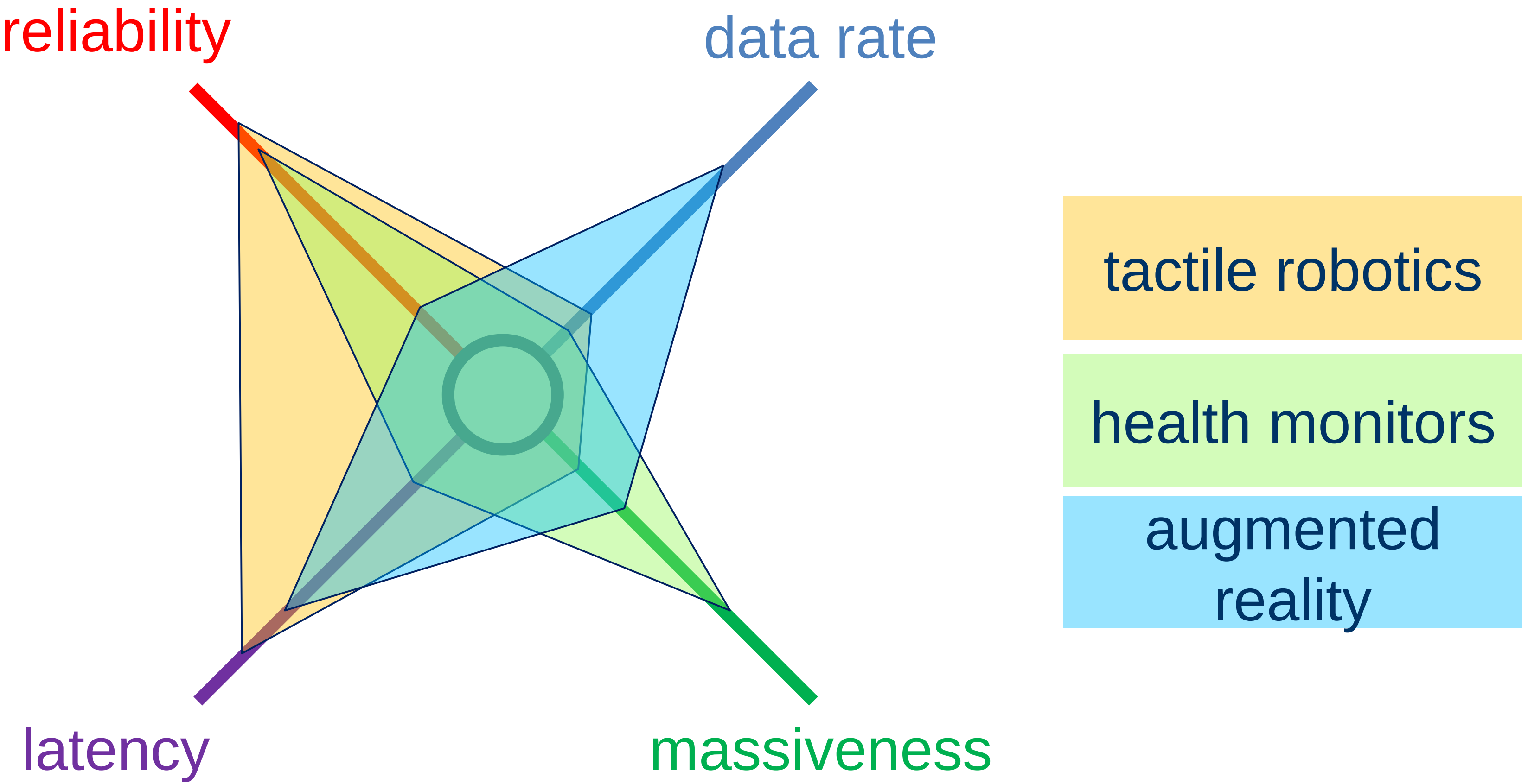
at least two cases for long-term URC

resilient connections with large latency budget

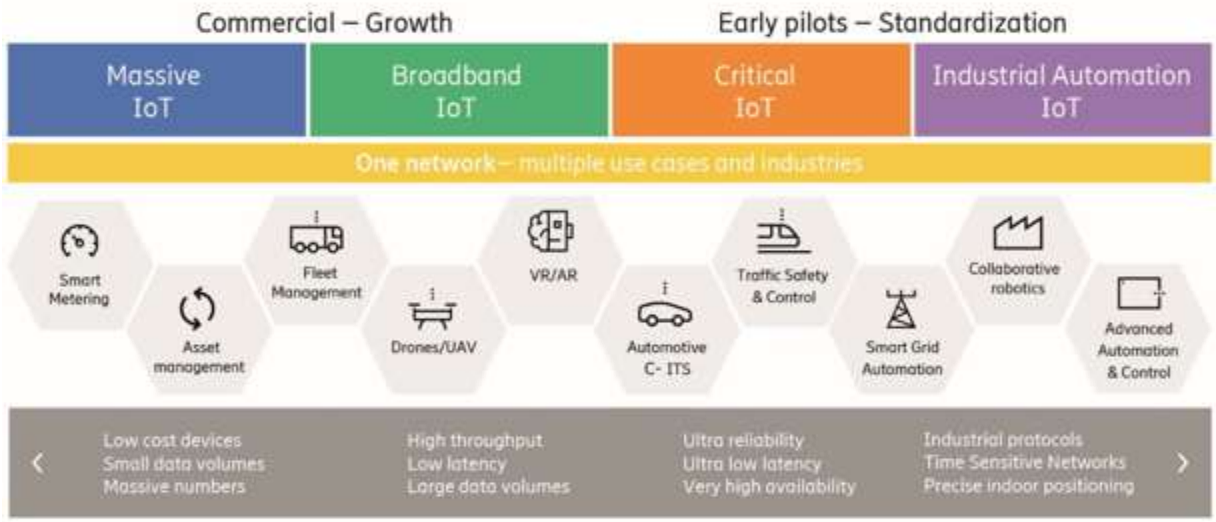
mobile health,
remote monitoring

disaster and rescue

connectivity space revisited

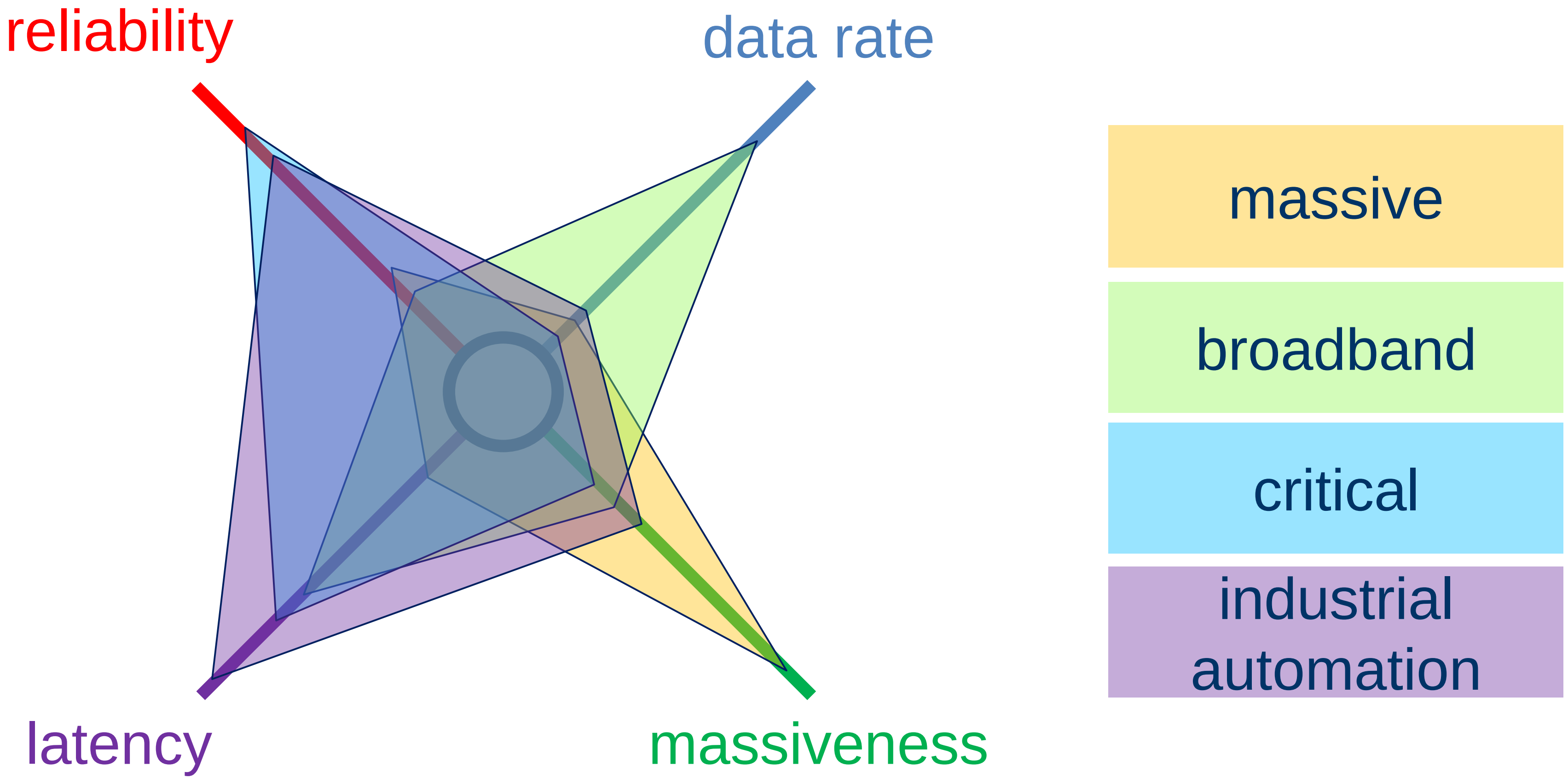


connectivity space of cellular IoT (Ericsson)



Ericsson, “Cellular IoT Evolution for Industry Digitalization,” white paper, 2019.

connectivity space of cellular IoT



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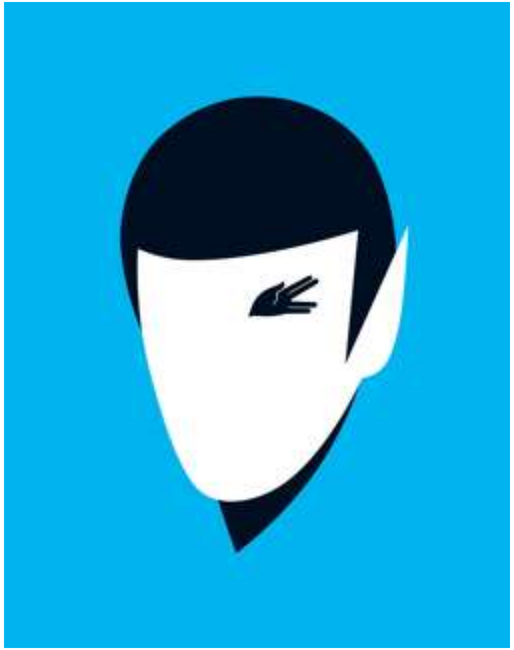
the power of modeling

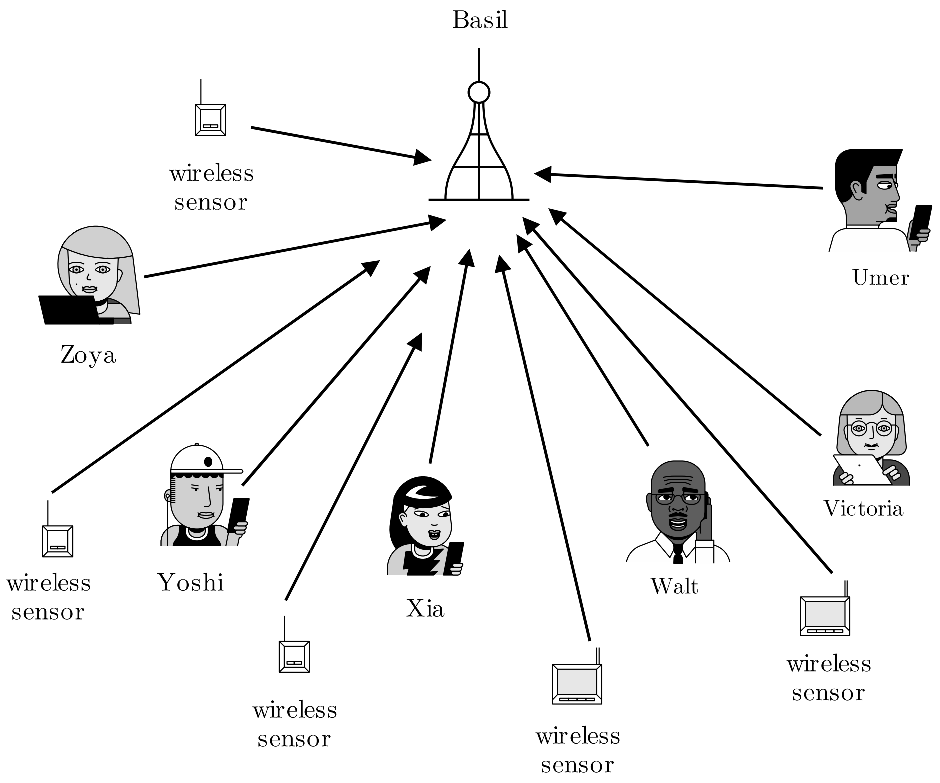
- a model is our representation of a real-life problem

- a model is a cartoon of reality,
  but as every good caricature,
  it contains sufficient features
  to recognize the person.

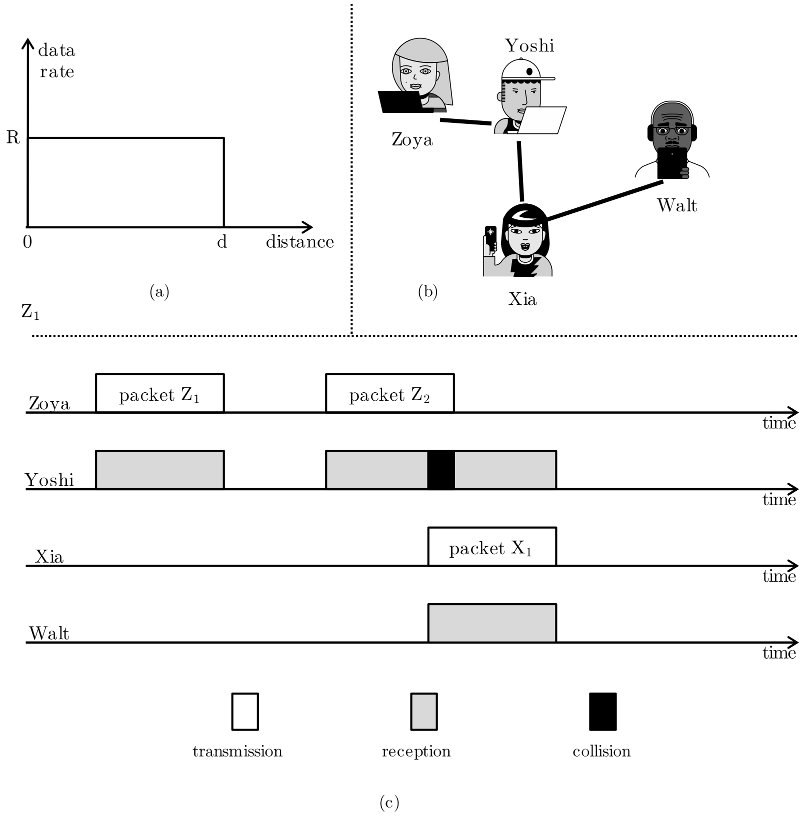


Spock by Noma Bar

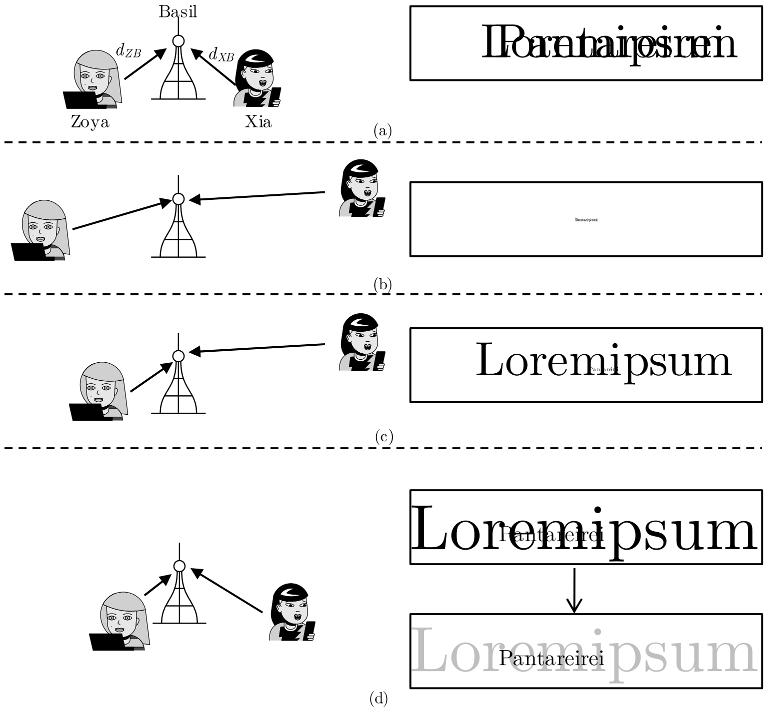
example: multiple access



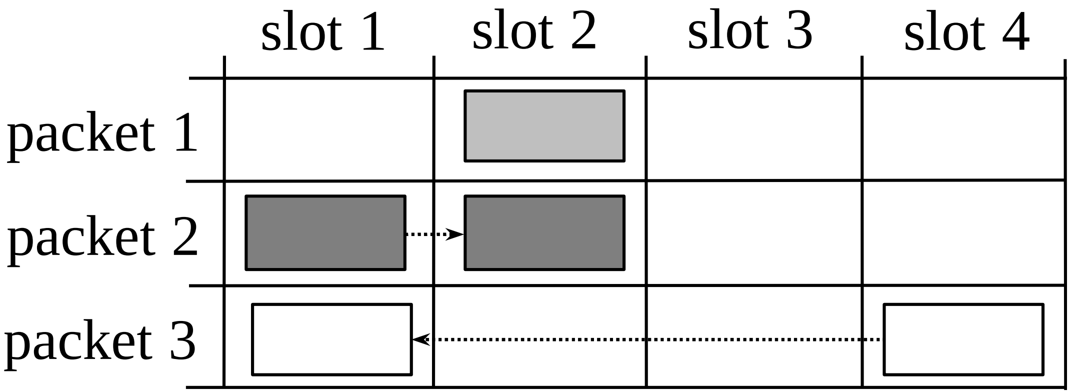
the simplest collision model



model enrichment: putting a distance

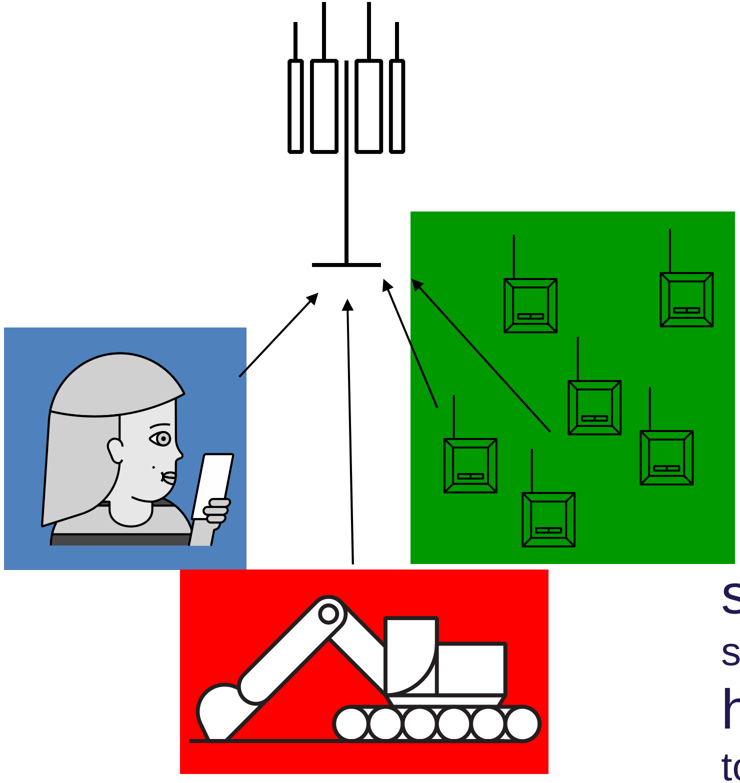


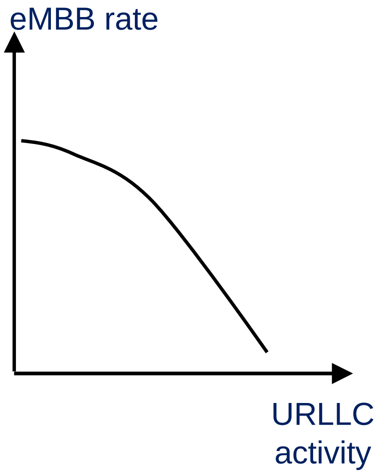
model enrichment: buffered collisions



leads to a coded random access!

heterogeneity adds a whole new dimension





slicing:

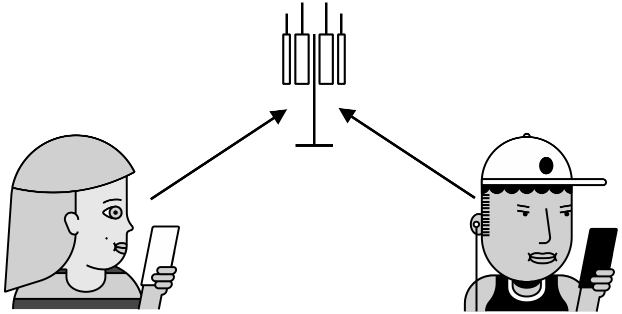
share the resource while providing

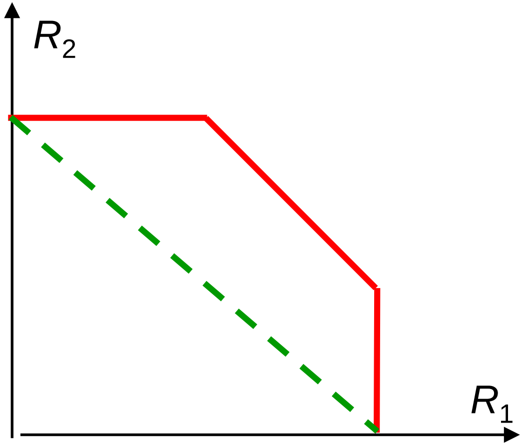
heterogeneous guarantees

to different services

the rationale behind the research potential of this model

classical multiple access channel (Ahlswede 1971, Liao 1972)





theoretical basis for

NOMA

Non-Orthogonal

Multiple Access

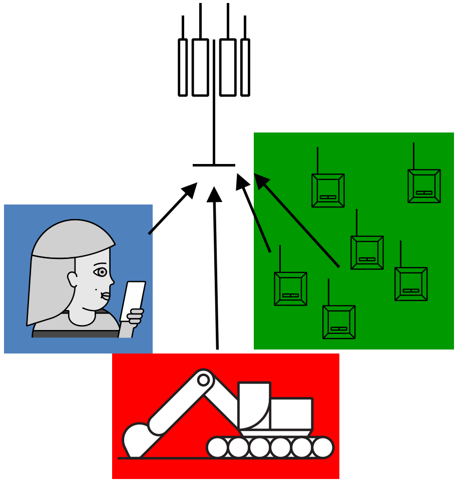
the more conventional

OMA

Orthogonal

Multiple Access

heterogeneous (5G) multiple access channel



the classical MAC model needs to be enriched for different

- traffic
- activation
- CSI knowledge
- requirements
- ...

heterogeneous NOMA (H-NOMA)

heterogeneous OMA (H-OMA)

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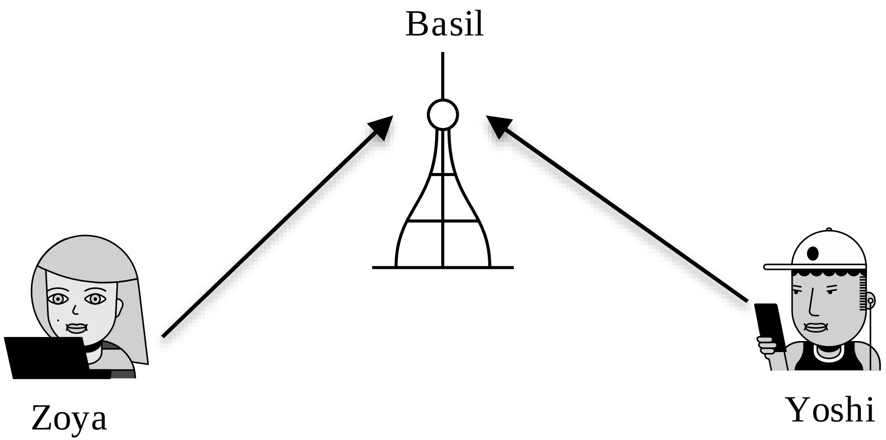
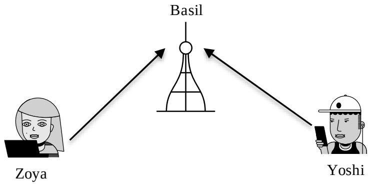
toy example on wireless slicing

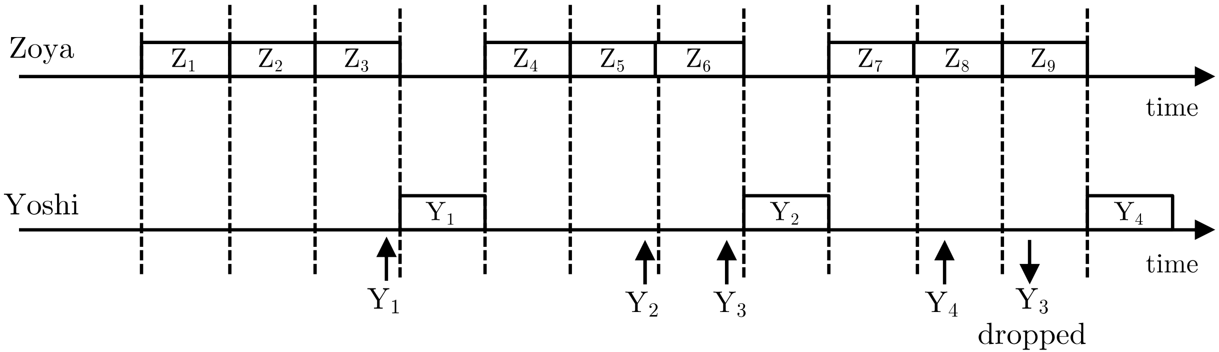


- broadband connectivity
- continuous transmission
- example: video stream
- target rate

- low-latency connectivity
- intermittent transmission
- example: reliable control
- target latency/reliability

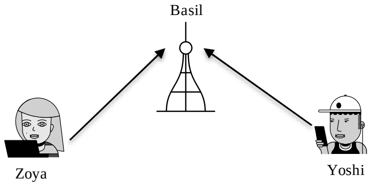
toy example: orthogonal slicing

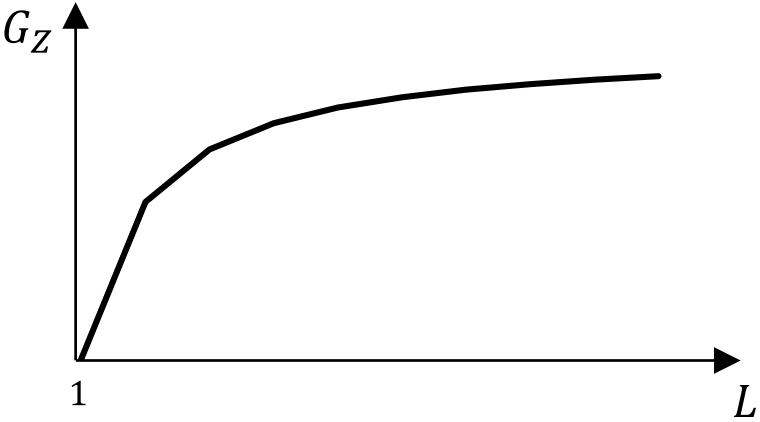




- L-th slot allocated to Yoshi
  - he waits at most L slots to deliver the packet
- the goodput of Zoya is $G_Z = \frac{L-1}{L} R$
- intermittency of Yoshi does not affect the goodput of Zoya

toy example: orthogonal slicing

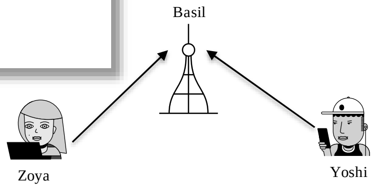


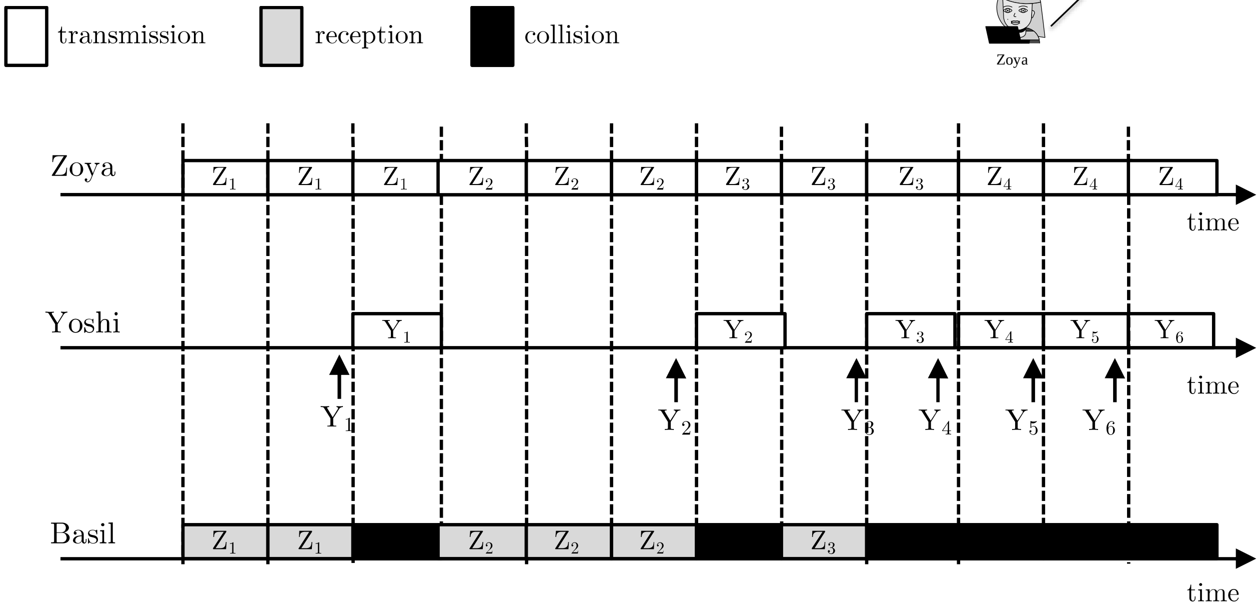


if Yoshi wants instantaneous transmission, then the goodput of Zoya is strictly 0.

what if the broadband connectivity can live with some error probability?

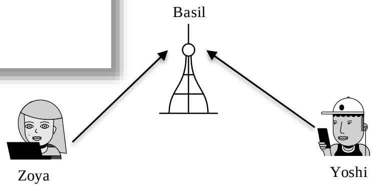
toy example: non-orthogonal slicing

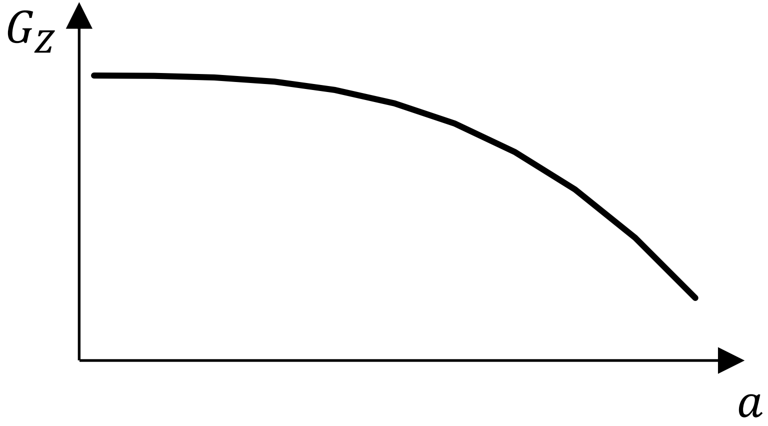




- Zoya repeats each packet 3 times
- Successive Interference Cancellation

toy example: non-orthogonal slicing





- error only if three repetitions are lost
- goodput of Zoya: $G_Z = \frac{R}{L}(1 - a^L)$

distilled 5G service requirements

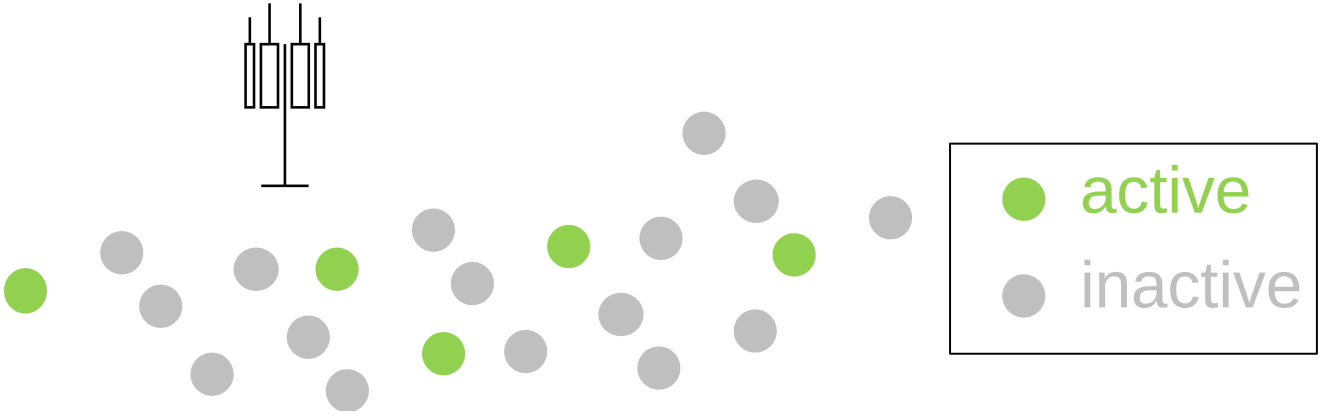
eMBB

- acceleration of 4G,
- large payloads, active over longer period
- scheduled users, no contention
- maximize rate, moderate reliability (e.g. 10E-3)

distilled 5G service requirements

mMTC

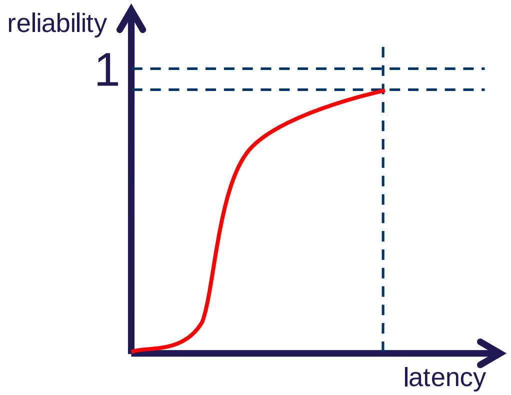
- fixed low rate
- unknown active subset from a massive device set
- maximize arrival rate, low reliability (e.g. 10E-1)



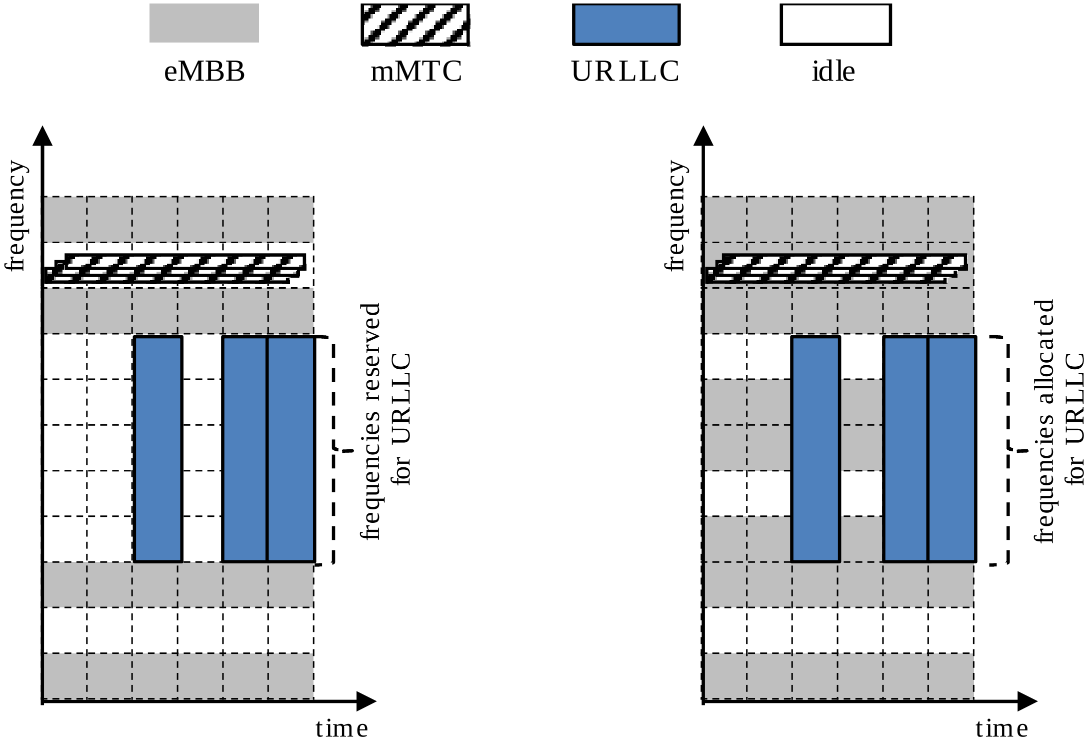
distilled 5G service requirements

URLLC

- intermittent transmissions, but from a much smaller device set
- offer high reliability (e.g. 10E-5), while localized in time
- use high level of diversity



two types of slicing

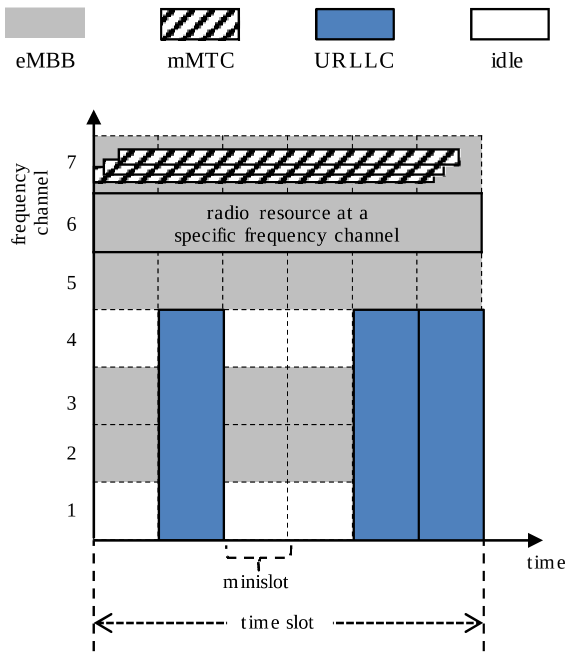


orthogonal

non-orthogonal

system model

- F frequency radio resources
- S minislots
- eMBB transmission takes one frequency resource
- a_U is the probability of active URLLC device in a minislot
- an URLLC transmission spreads over F_U frequencies
- A_M is the Poisson-distributed number of active mMTCs



the received signal in a minislot

$$\mathbf{Y}_{s,f} = H_{B,f}\mathbf{X}_{B,f} + H_{U,f}\mathbf{X}_{U,s,f} + \sum_{m=1}^{A_M} H_{[m],f}\mathbf{X}_{[m],s,f} + \mathbf{Z}_{s,f}$$

not a classical multiple access channel

- different arrivals, different decoding criteria, etc.

independent Rayleigh-faded $H_{i,f}$

if there is no transmission, $\mathbf{X}_{i,f} = 0$

some more bits and pieces about the model

eMBB

- has a full CSI and transmits with channel inversion
- not transmitting w.p. $1 - a_B$ results in outage

$$r_{B,f} = \log_2\left(1 + G_{B,f}^{\mathrm{tar}}\right)$$

URLLC

- find maximal rate r_U that satisfies ε_U
- no CSIT and no power adaptation

$$\Pr(E_U) = \Pr\left(\frac{1}{F_U}\sum_{f=1}^{F_U}\log_2\left(1 + G_{U,f}\right) < r_U\right) \leq \varepsilon_U$$

some more bits and pieces about the model

mMTC: use of successive interference cancellation (SIC)

SNRs: $G_{[1]} \geq G_{[2]} \geq \cdots \geq G_{[A_M]}$

SINR: $\sigma_{[m_0]} = \frac{G_{[m_0]}}{1+\sum_{m=m_0+1}^{A_M} G_{[m]}}$

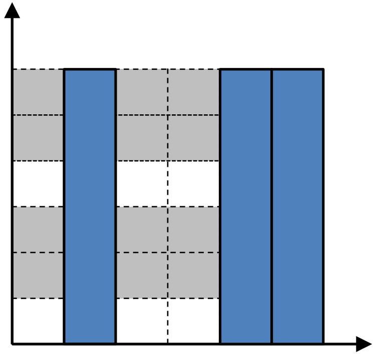
decoding condition: $\log_2\left(1+\sigma_{[m_0]}\right) \geq r_M$

the reliability diversity

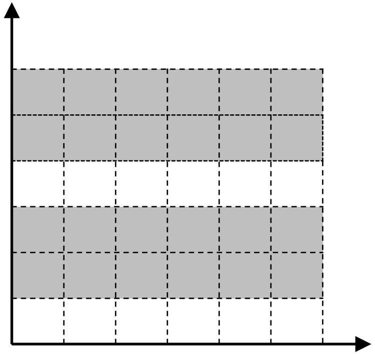
$$\varepsilon_U \ll \varepsilon_B \ll \varepsilon_M$$

design that benefit from heterogeneous reliability requirements

example of interfering eMBB and URLLC:



$(1-\varepsilon_U)$



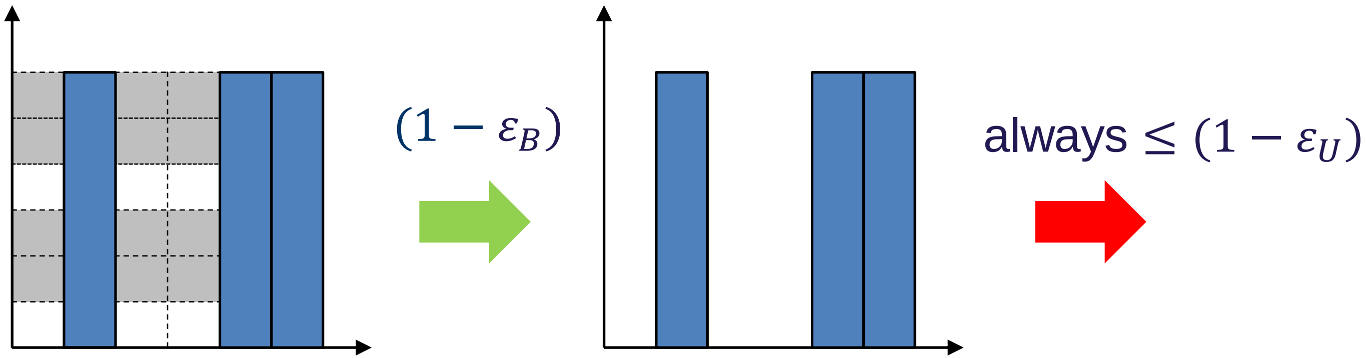
$$(1-\varepsilon_U)(1-\varepsilon_B') \geq (1-\varepsilon_B)$$

the reliability diversity

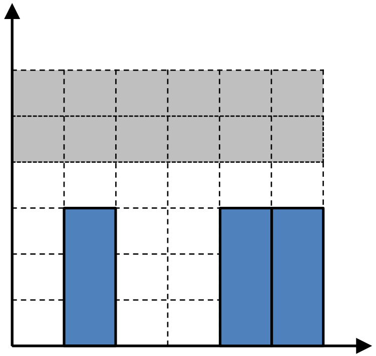
$$\varepsilon_U \ll \varepsilon_B \ll \varepsilon_M$$

design that benefit from heterogeneous reliability requirements

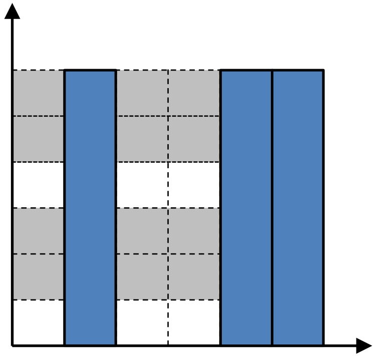
example of interfering eMBB and URLLC:



slicing for eMBB and URLLC



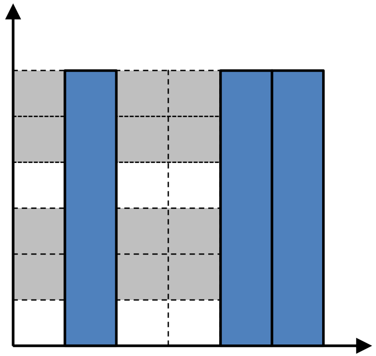
orthogonal



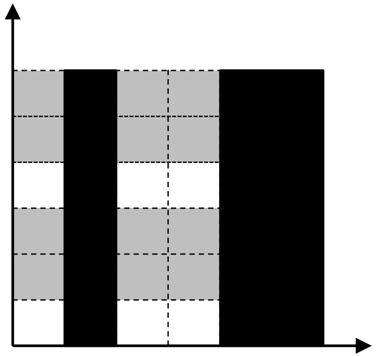
non-orthogonal
with SIC

$$\Pr\left(\frac{1}{F_U}\sum_{f=1}^{F_U}\log_2\left(1+\frac{G_{U,f}}{1+G_{B,f}^{\mathrm{tar}}}\right)<r_U\right)\leq\varepsilon_U$$

slicing for eMBB and URLLC



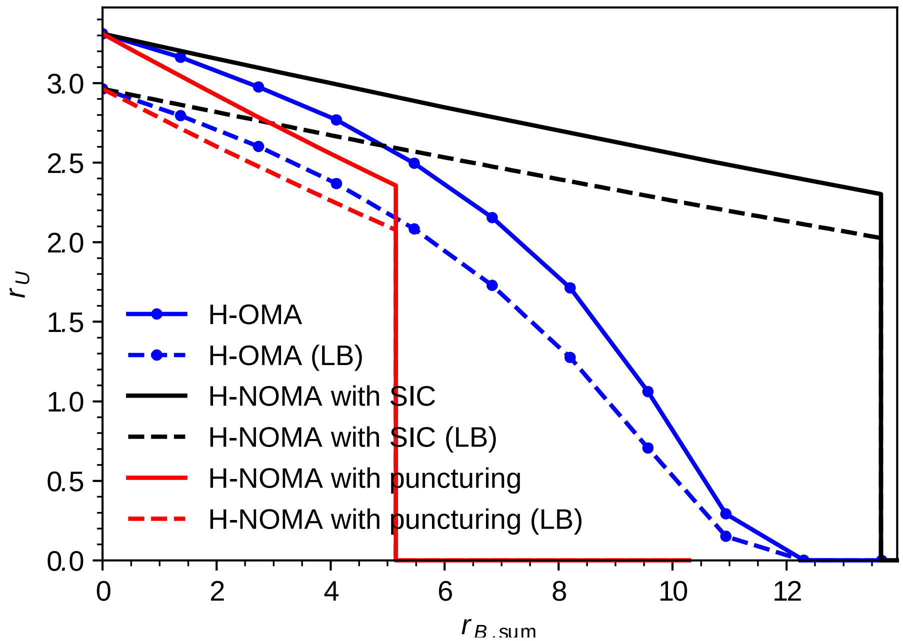
non-orthogonal
with puncturing



perspective of the
eMBB

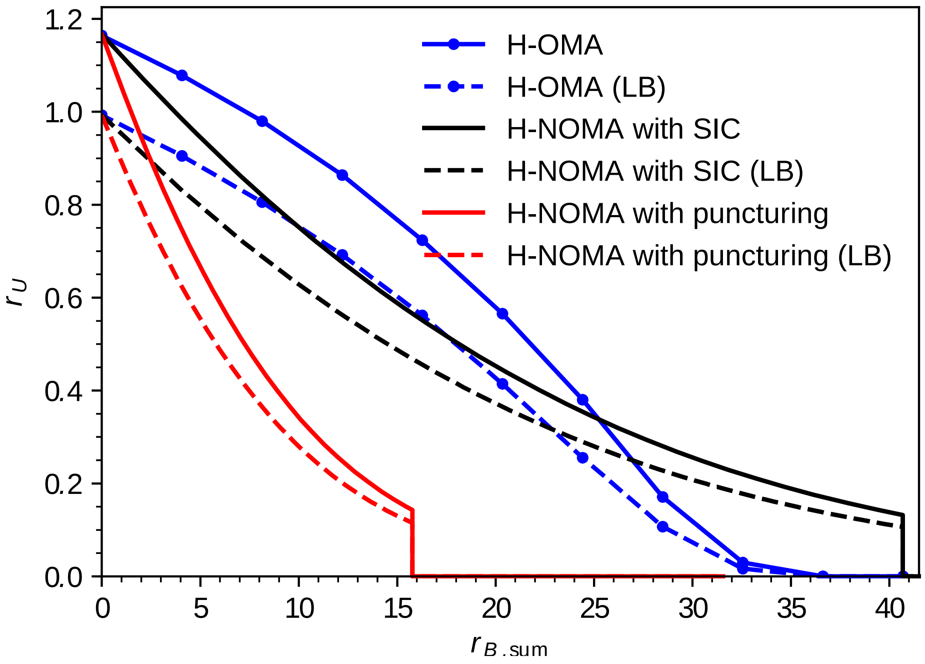
eMBB uses erasure code of rate $1-\frac{k}{S}$
and thus has a decreased rate

slicing for eMBB and URLLC: results



$$\Gamma_U > \Gamma_B$$

slicing for eMBB and URLLC: results



$$\Gamma_U < \Gamma_B$$

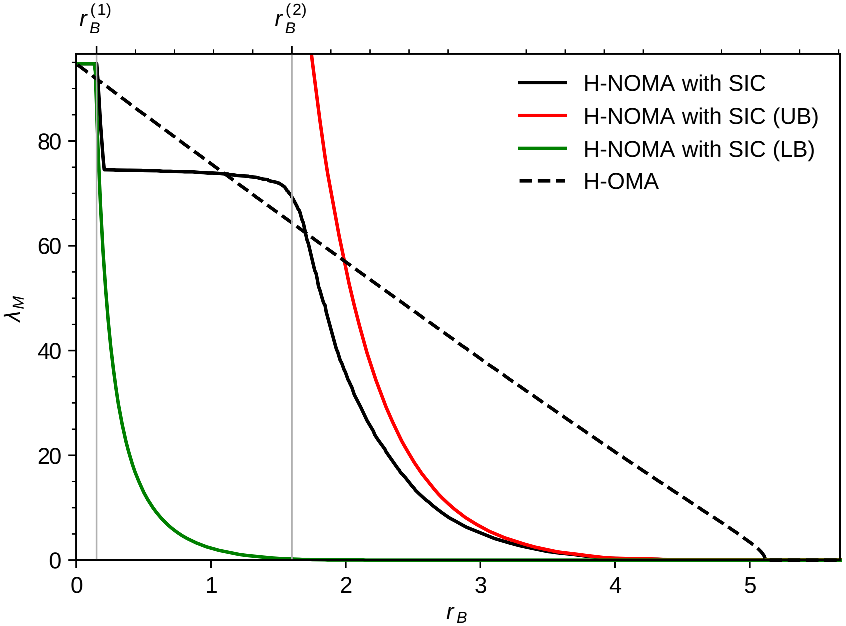
slicing for eMBB and mMTC

we look into a single radio frequency resource

- **orthogonal** slicing achieved by time-sharing
- **non-orthogonal** slicing achieved by SIC

SINR: $$\sigma_{[m_0]} = \frac{G_{[m_0]}}{1+G_{B,f}^{\mathrm{tar}}+\sum_{m=m_0+1}^{A_M} G_{[m]}}$$

slicing for eMBB and mMTC: results



three regimes

(1) small r_B (2) intermediate r_B

(3) large r_B

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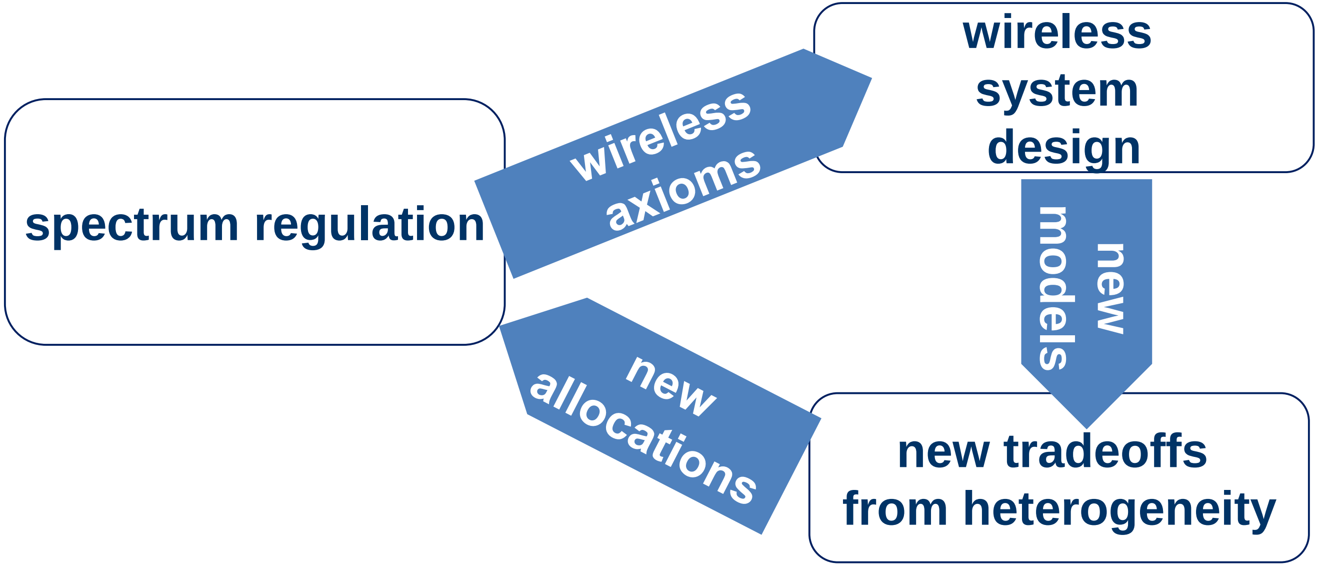
outlook: impact on spectrum usage



final remarks

- future connectivity will be characterized by vast heterogeneity of features and requirements
  - should AI algorithms tell us how to segment this heterogeneity?
- trading off heterogeneous requirements, complex allocation of resources
- communication-theoretic models essential in getting new insights

recent references

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