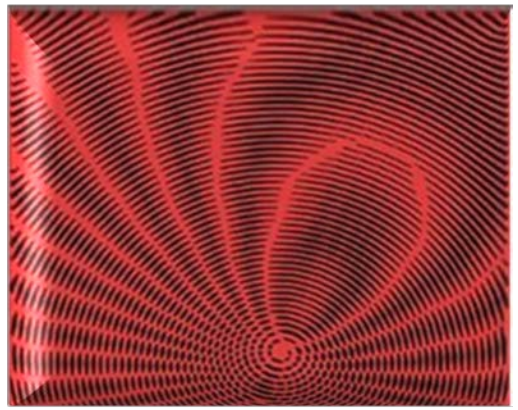
OPTCOM

Non-linearity Modeling at Ultra-high Symbol Rates



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Thanks!

- To:
  - **CISCO Photonics**
  - the **PhotoNext Center** of Politecnico di Torino

  for supporting the research

- To **Stefano Piciaccia, Chris Fludger, Alberto Tanzi, Marco Mazzini** and many others from CISCO Photonics for the guidance and useful discussions

- To **Mattia Cantono** for his invaluable help in setting up and tuning the servers and GPUs

- Fiber non-linearity modeling has made a lot of progress since the beginning of the ‘coherent era’

- We now have several non-linear interference (NLI) models
  - time-domain
  - GN/EGN
  - pulse collision
  - logarithmic perturbation
  - … many others

  for comprehensive references, see for instance:
  P. Poggiolini, Y. Jiang “Recent Advances in the Modeling of the Impact of Nonlinear Fiber Propagation Effects on Uncompensated Coherent Transmission Systems,” Tutorial Review, J. of Lightw. Technol., vol. 35, no. 3, pp. 458-480, Feb. 2017.

- They are currently in wide use for the study, design and real-time management of optical transmission networks…
- …because they appear to work well, within their respective range of validity

- *Lately, though, several disruptive **strong industry trends** have shown up*

- One current strong industry trend is to move swiftly towards higher rates
  - 64 GBaud is here now
  - 96-128 are around the corner
  - maybe in the future 256 GBaud ? higher ?
- *How do NLI models hold up at these super-high rates ?*

- Further strong trends:
  - **high-cardinality constellations** → up to 256 QAM
  - **Gaussian-shaped constellations** → rapidly going commercial
  - **replacement of pre-FEC BER with MI/GMI** for system study, design, even monitoring
- *How do NLI models hold up in these new contexts ?*

- We decided to investigate to find out…

What we investigated

- We did extensive GN/EGN model testing vs. simulations:
  - sweeping symbol rates from 8 GBaud up to **512 GBaud**
  - with high-cardinality constellation: **32, 64, 128 , 256 PM-QAM**
  - including ideal **Gaussian** constellations in the study
  - using **MI/GMI** for performance assessment

- *so we actually addressed all the industry trends mentioned before*

- In practice, we compared in those new scenarios:
  - the system Maximum Reach obtained using the **GN/EGN model**
  - with the system Maximum Reach found through **split-step simulations**

to see how accurate the prediction was

How is Max Reach found?

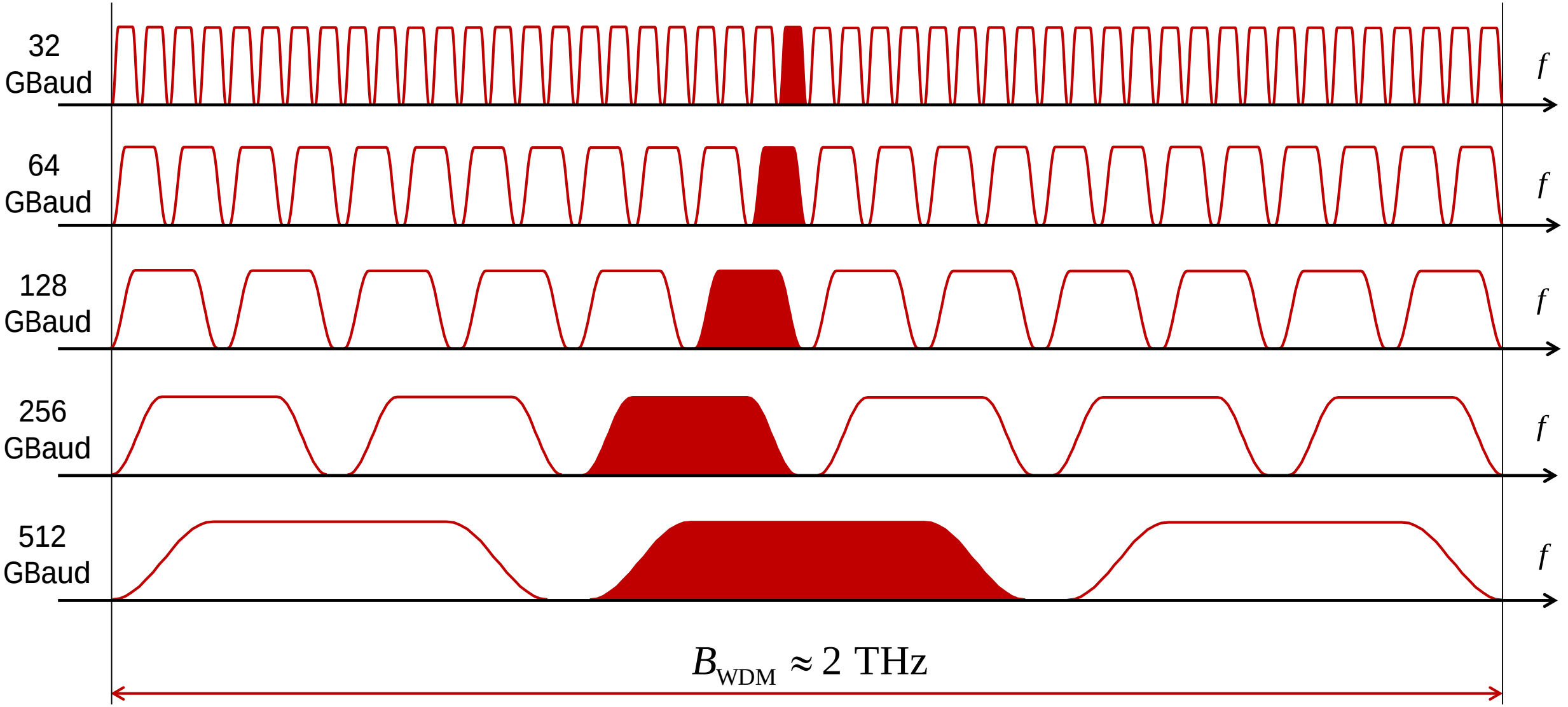
- How is System Maximum Reach found?
  - the maximum reach for a system is
    the distance where its MI/GMI goes below a set threshold
    (with optimized launch power)

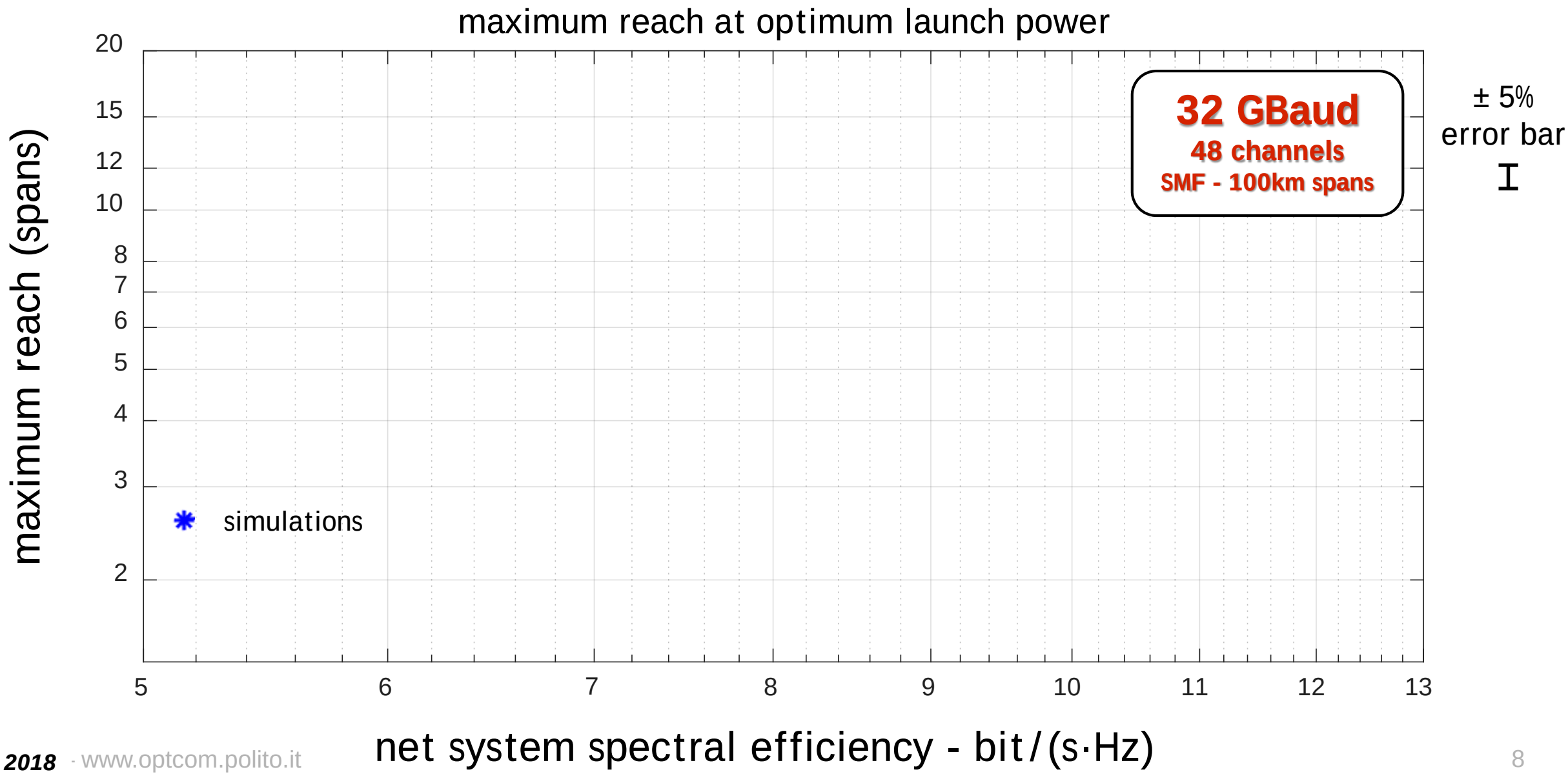
- For all formats the MI/GMI threshold was chosen as 87% of the constellation entropy
  - for reference, 87% of entropy corresponds to about 15% coding overhead

- for instance: PM-64QAM → (12 bits/symb) x 87% = 10.44 bits/symb
- that is, **the GMI threshold for PM64QAM was set to 10.44 bits/symb**

- Other relevant system features common to all systems and formats:
  - SMF, 100 km spans
  - EDFA NF 6dB
  - root-raised-cosine channels with roll-off 0.2
  - **Rx is ideal (perfect equalization and laser PN compensation),**
    but does not make any attempt at mitigating non-linear phase noise (NLPN)

very different scenarios…




maximum reach at optimum launch power
maximum reach (spans)
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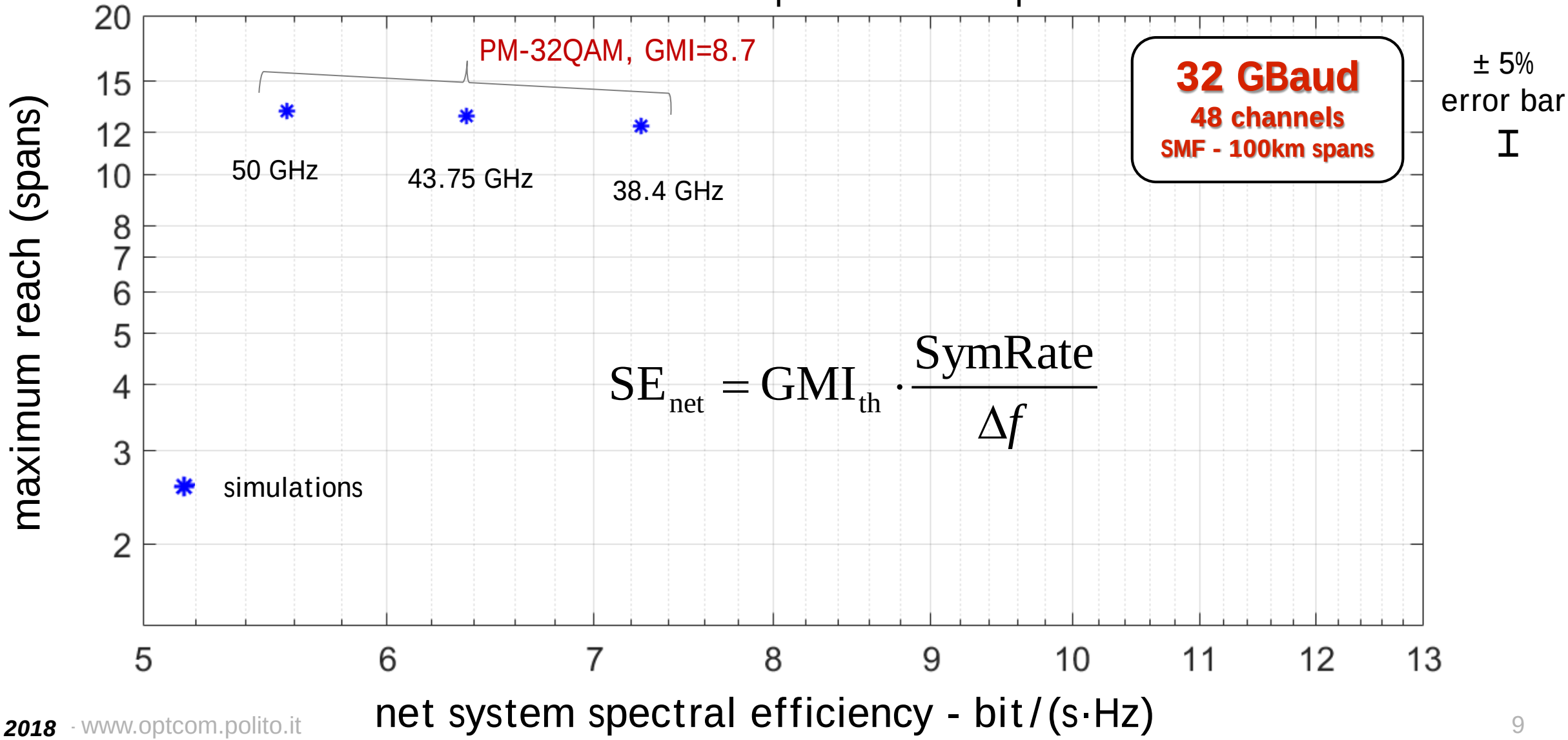
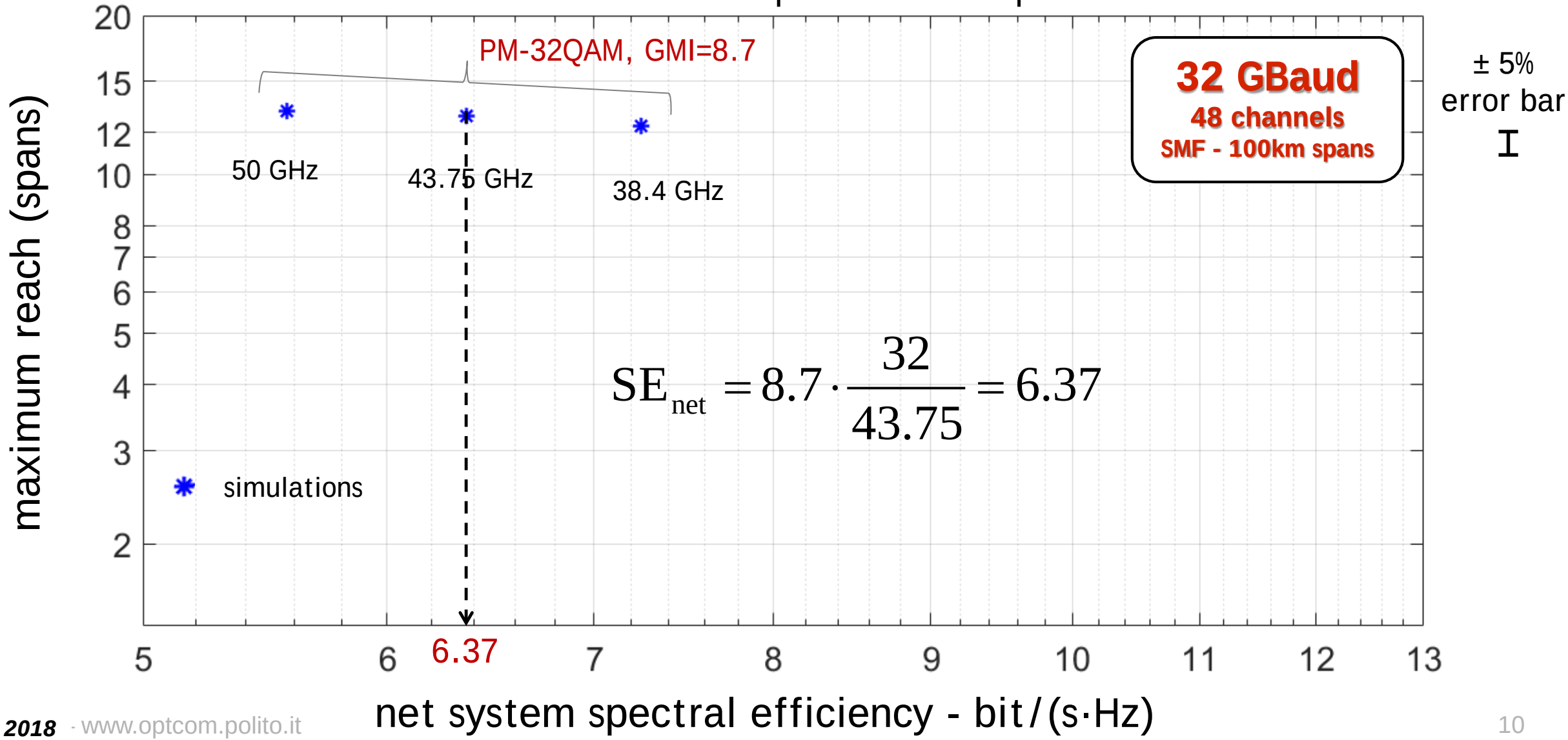
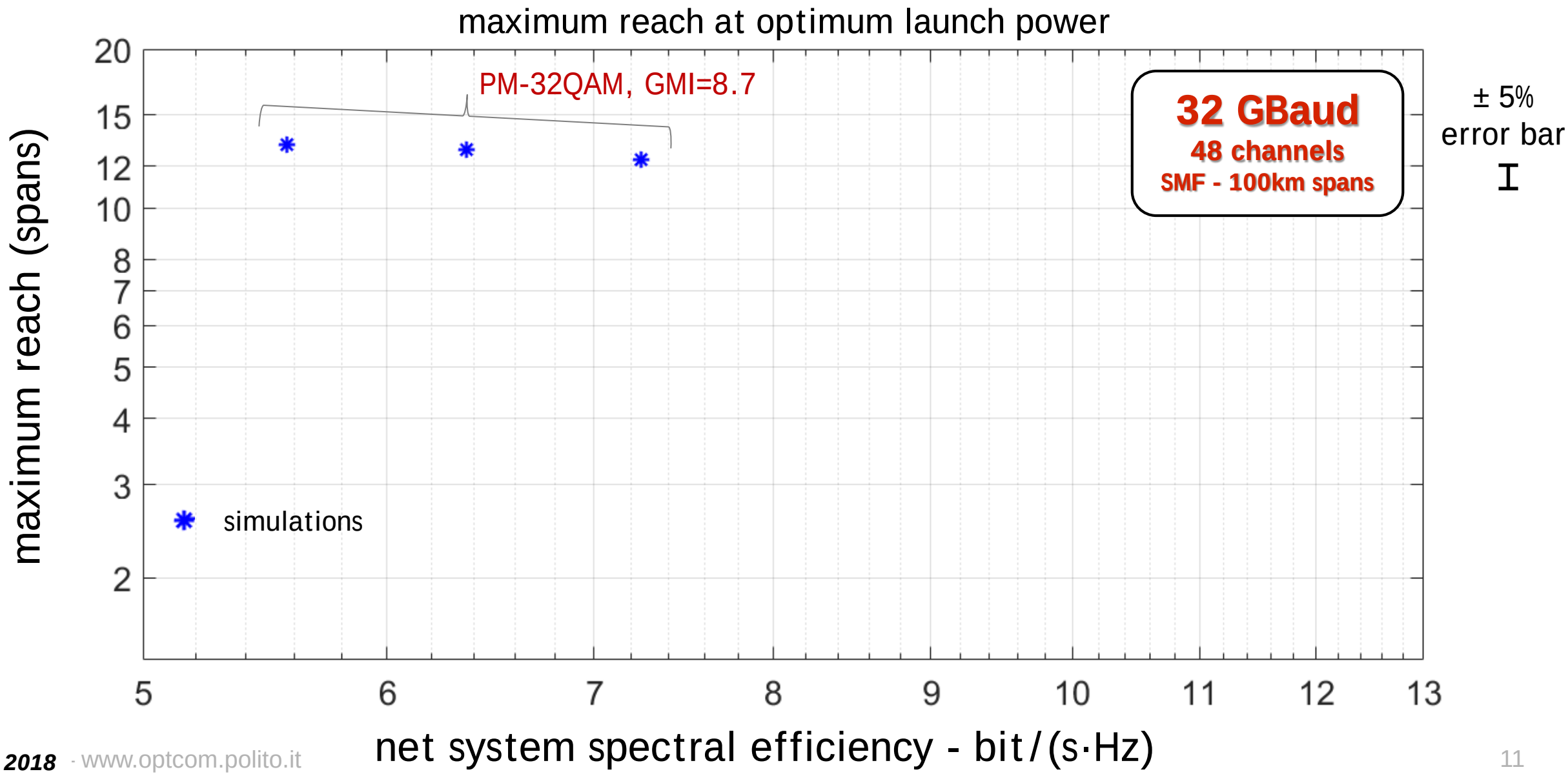
net system spectral efficiency - bit/(s·Hz)
32 GBaud
48 channels
SMF - 100km spans
simulations
± 5%
error bar

maximum reach at optimum launch power



maximum reach at optimum launch power




maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM, GMI=8.7
simulations
32 GBaud
48 channels
SMF - 100km spans
± 5%
error bar
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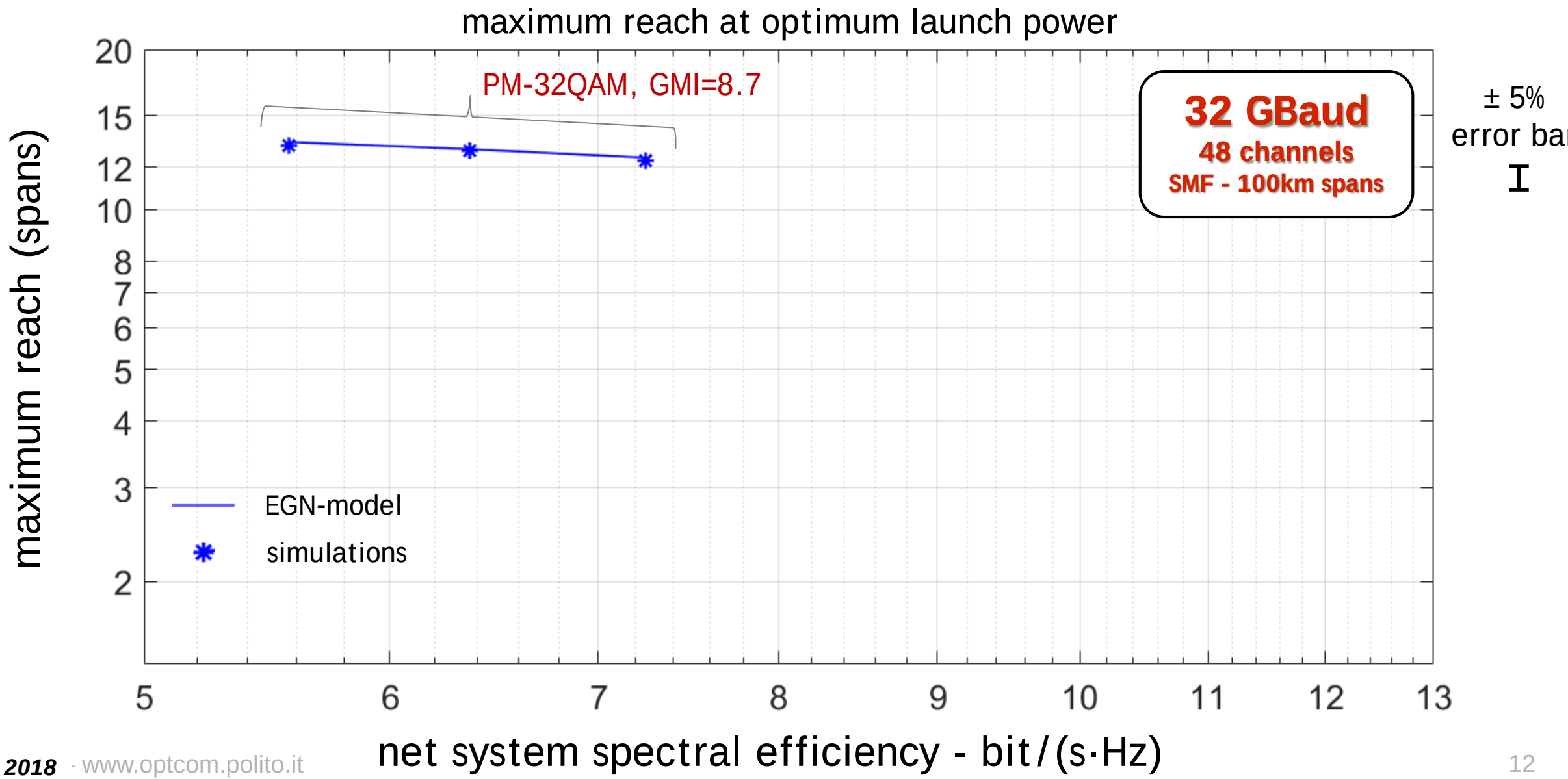
maximum reach at optimum launch power
PM-32QAM, GMI=8.7
32 GBaud
48 channels
SMF - 100km spans
± 5%
error bar
EGN-model
simulations
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
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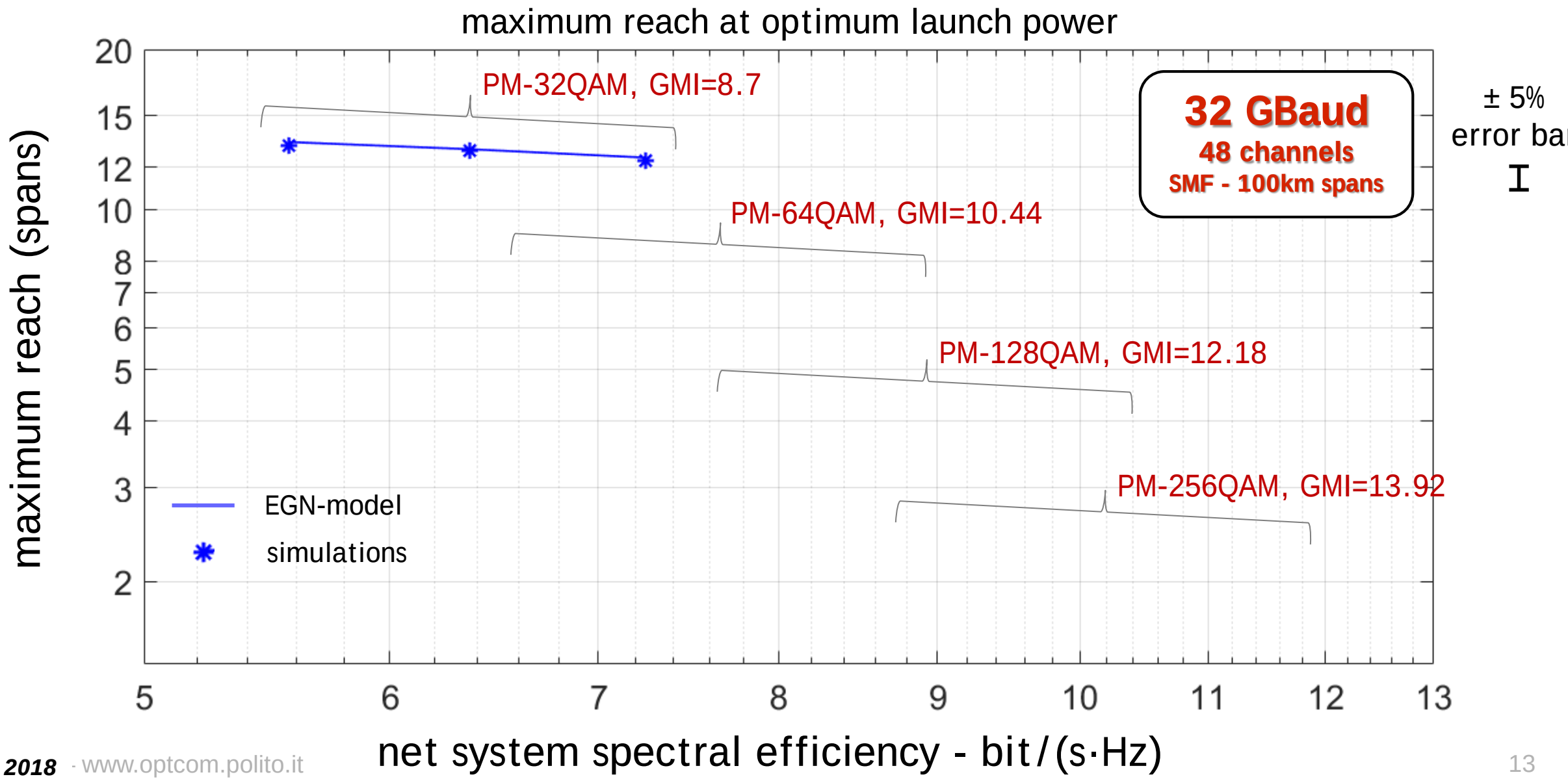
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM, GMI=8.7
PM-64QAM, GMI=10.44
PM-128QAM, GMI=12.18
PM-256QAM, GMI=13.92
32 GBaud
48 channels
SMF - 100km spans
EGN-model
simulations
± 5%
error bar
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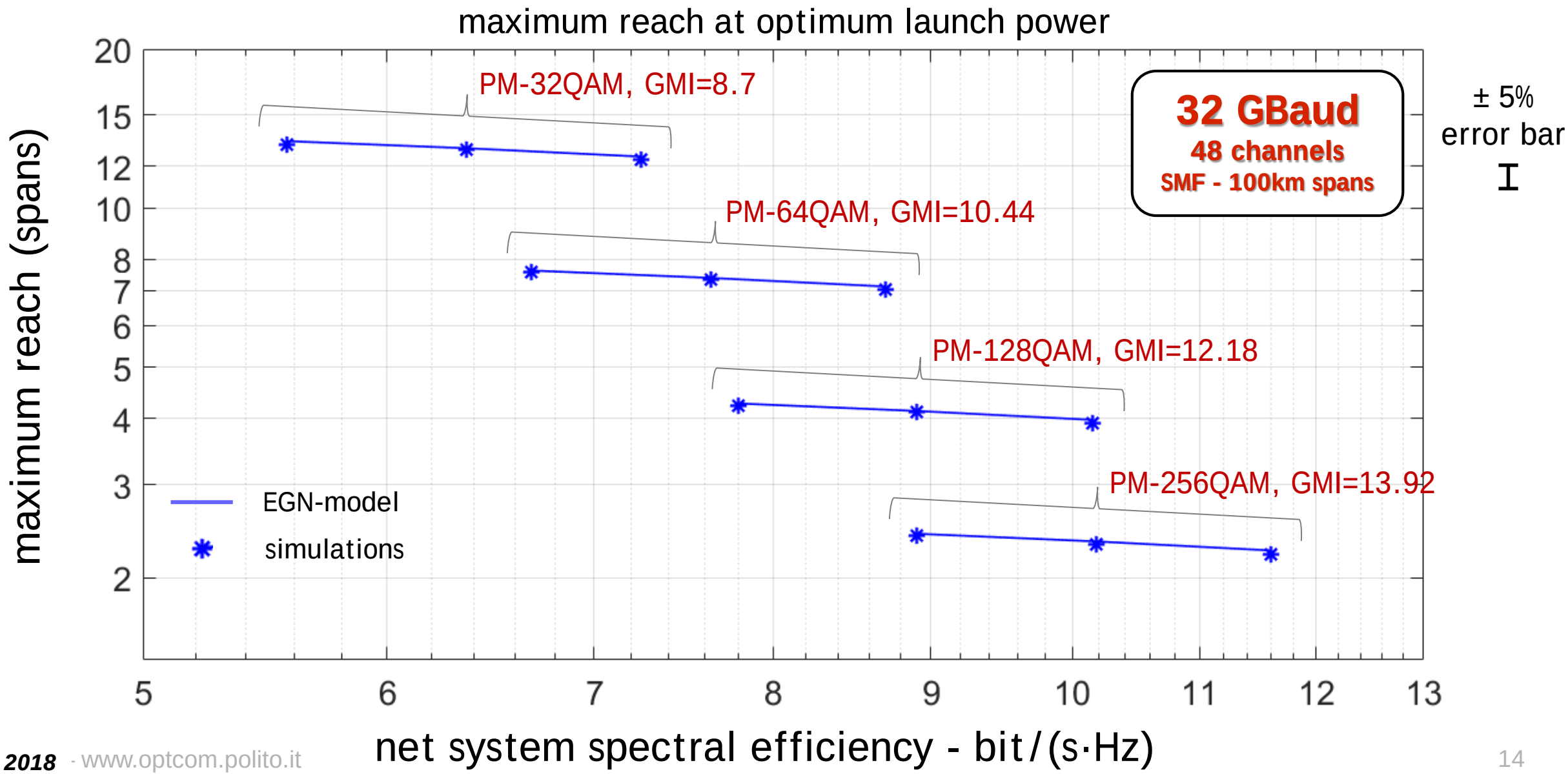
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM, GMI=8.7
PM-64QAM, GMI=10.44
PM-128QAM, GMI=12.18
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48 channels
SMF - 100km spans
EGN-model
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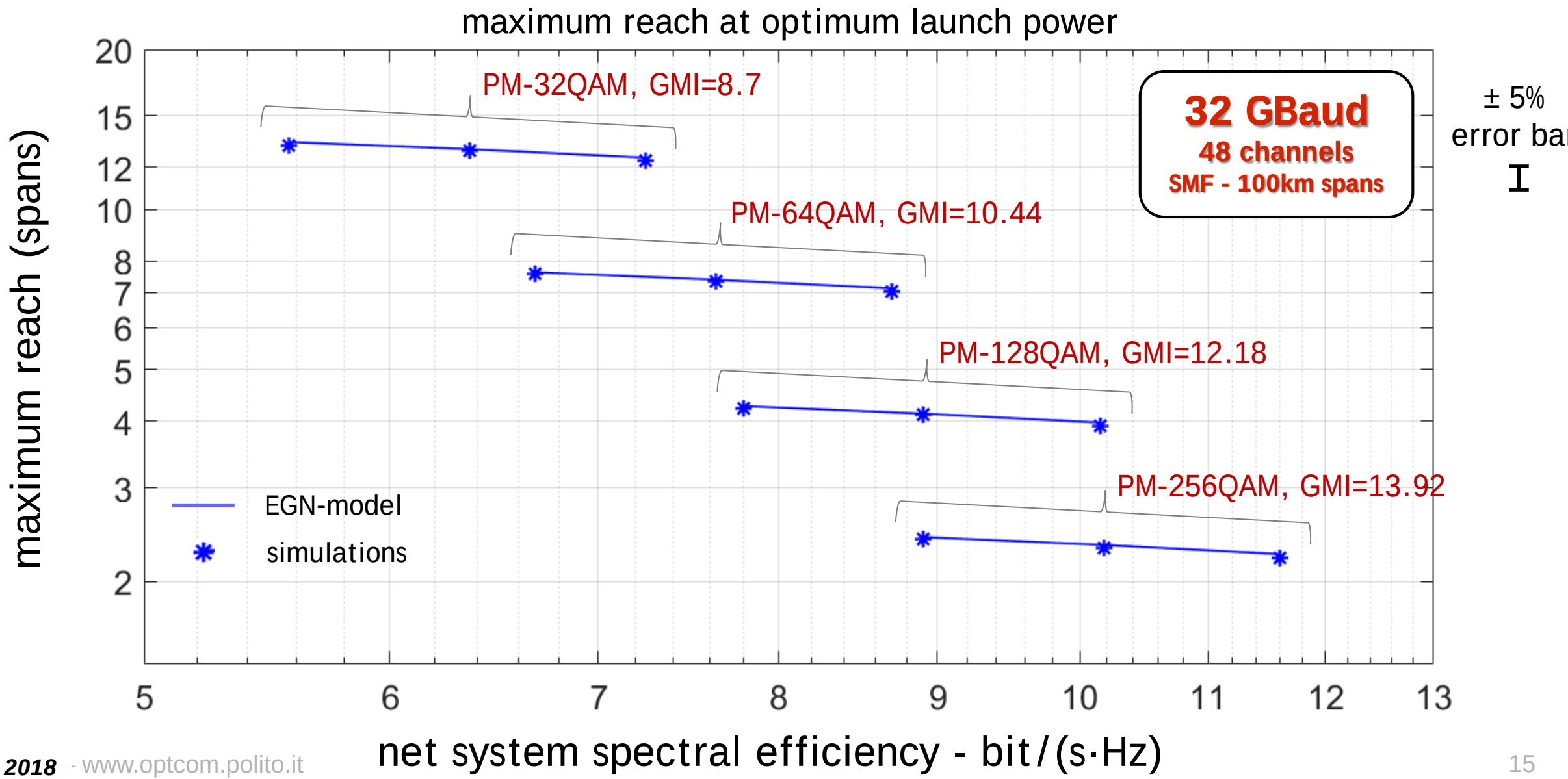
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM, GMI=8.7
PM-64QAM, GMI=10.44
PM-128QAM, GMI=12.18
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SMF - 100km spans
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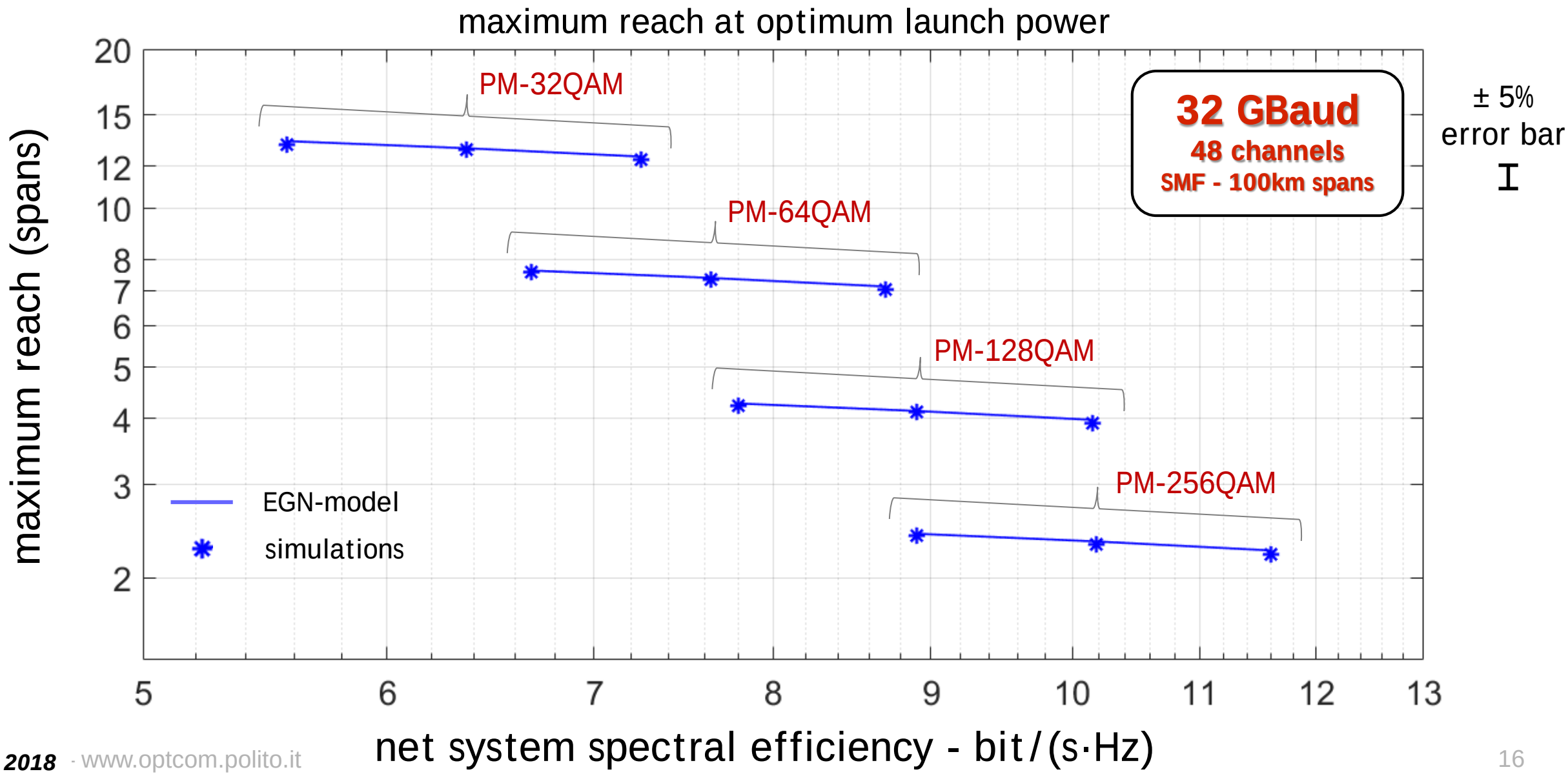
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
32 GBaud
48 channels
SMF - 100km spans
EGN-model
simulations
± 5%
error bar
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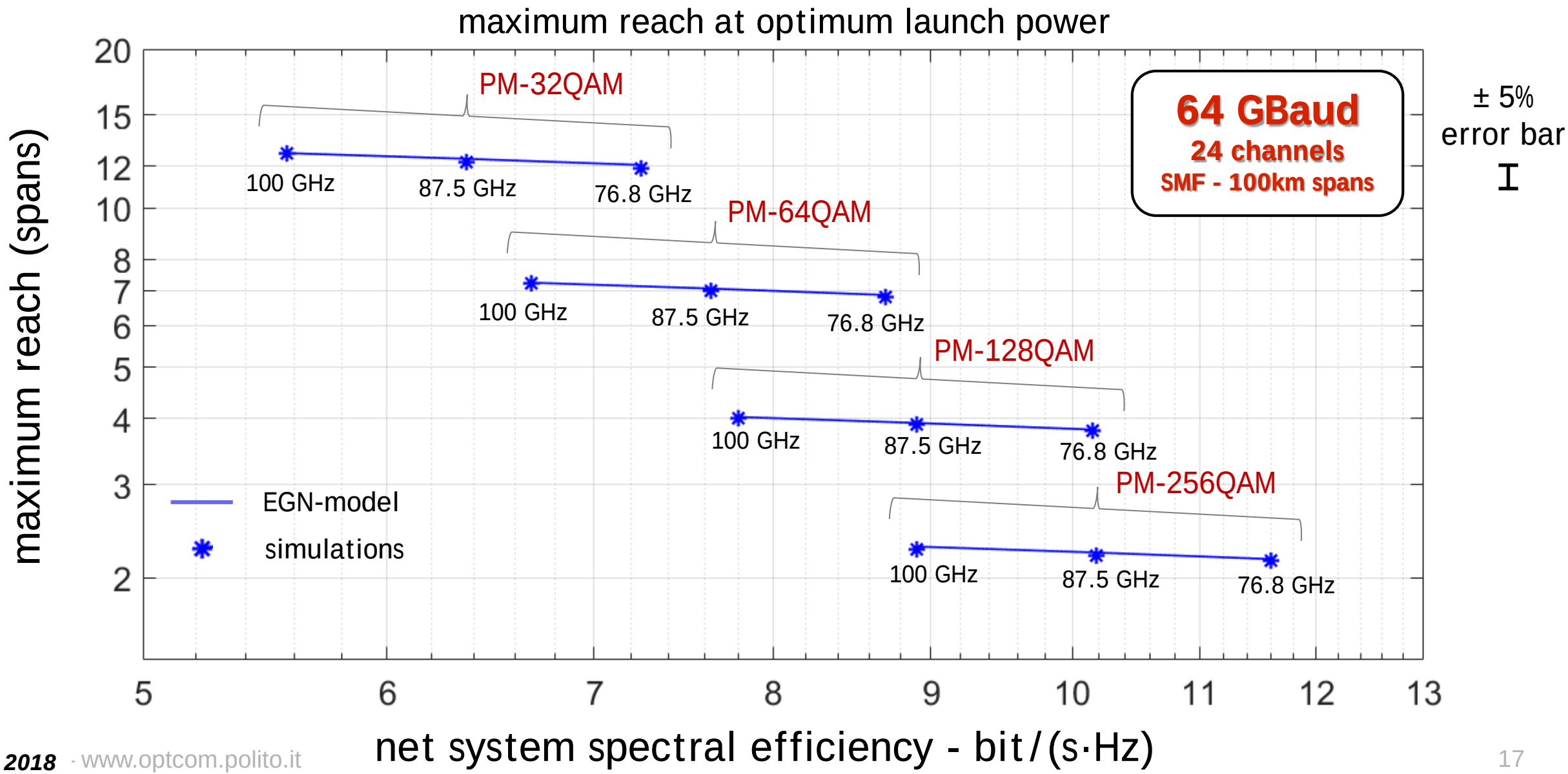
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
100 GHz
87.5 GHz
76.8 GHz
64 GBaud
24 channels
SMF - 100km spans
± 5%
error bar
EGN-model
simulations
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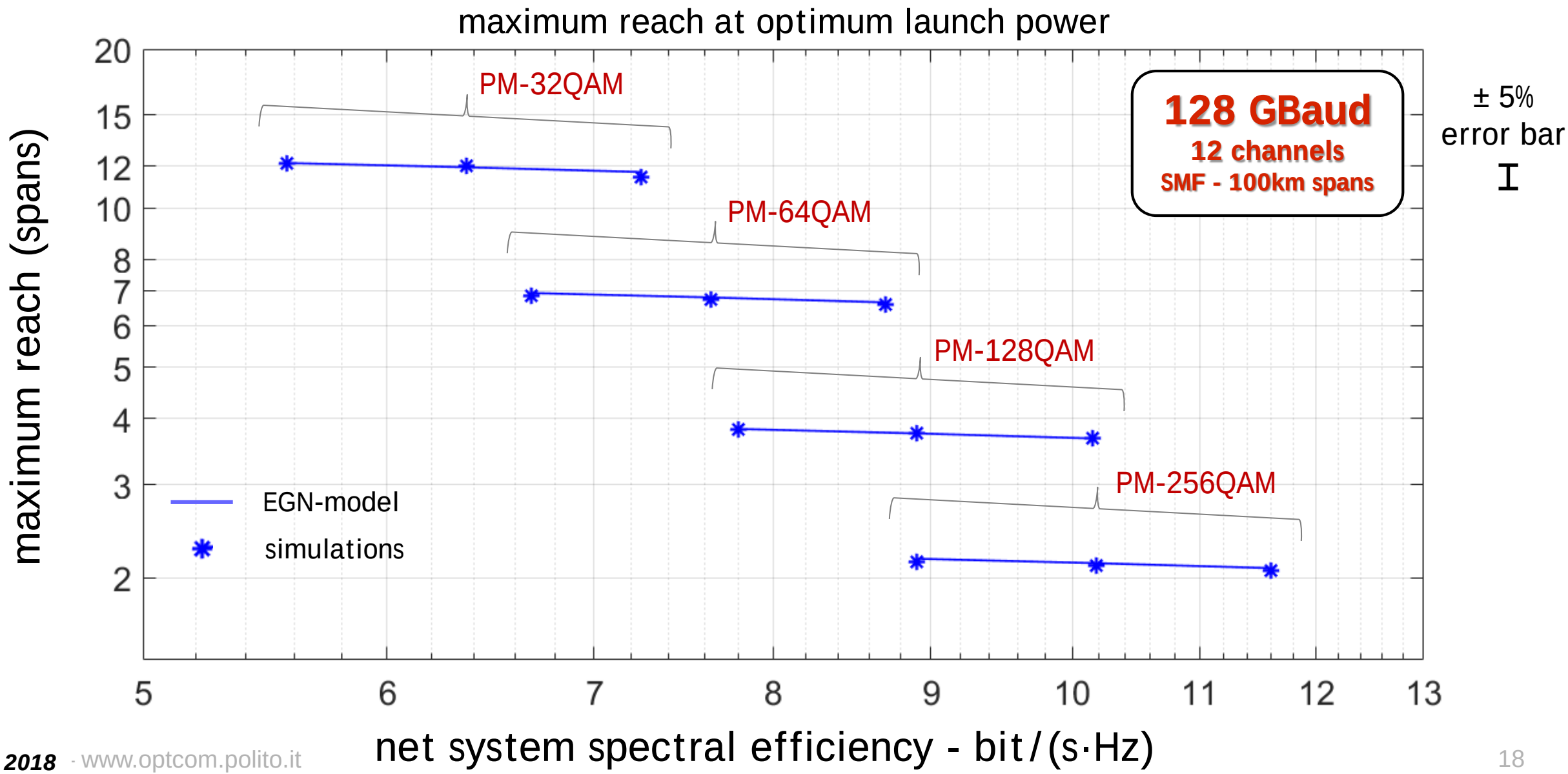
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
128 GBaud
12 channels
SMF - 100km spans
± 5%
error bar
EGN-model
simulations
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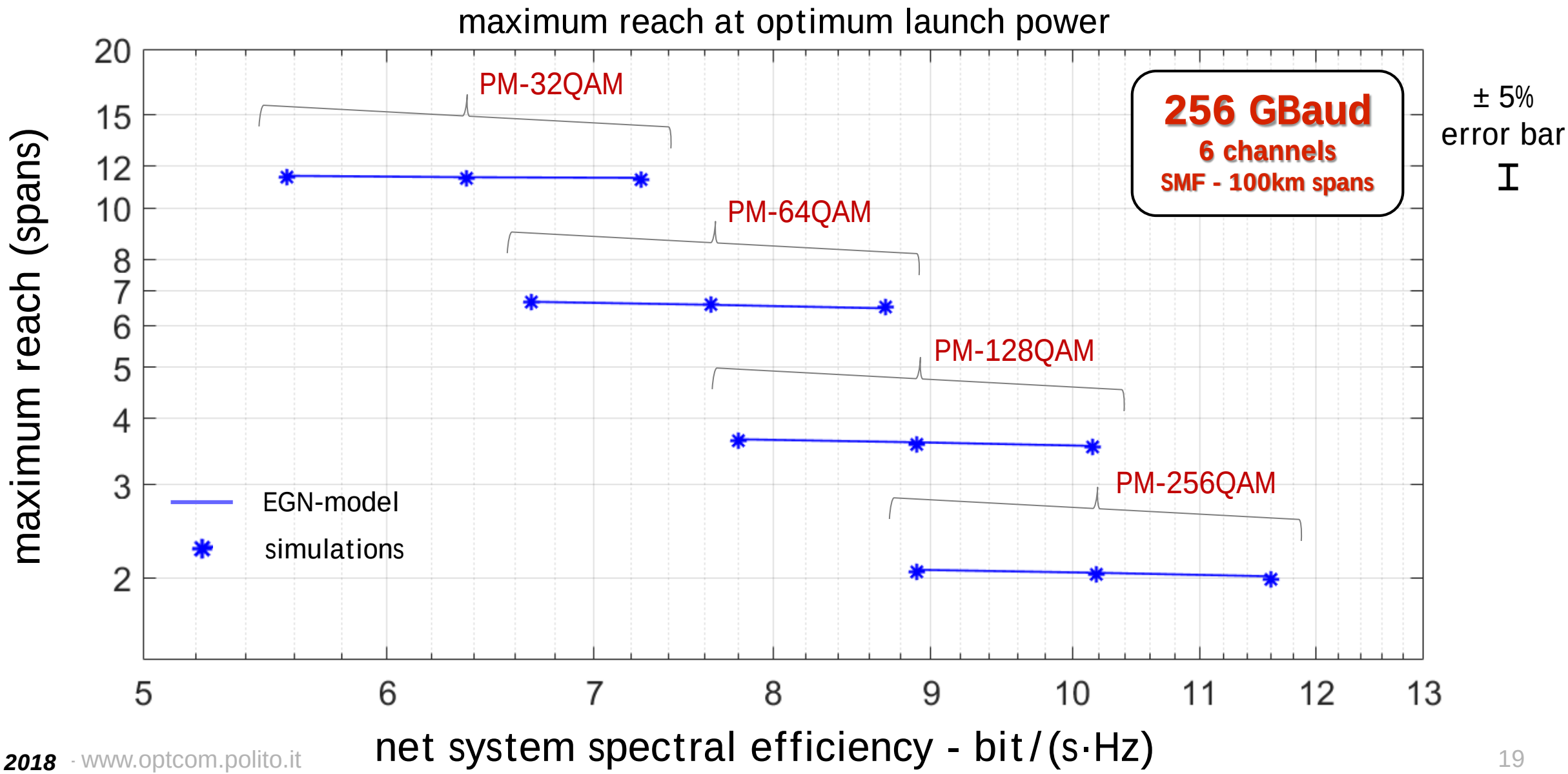
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
256 GBaud
6 channels
SMF - 100km spans
± 5%
error bar
EGN-model
simulations
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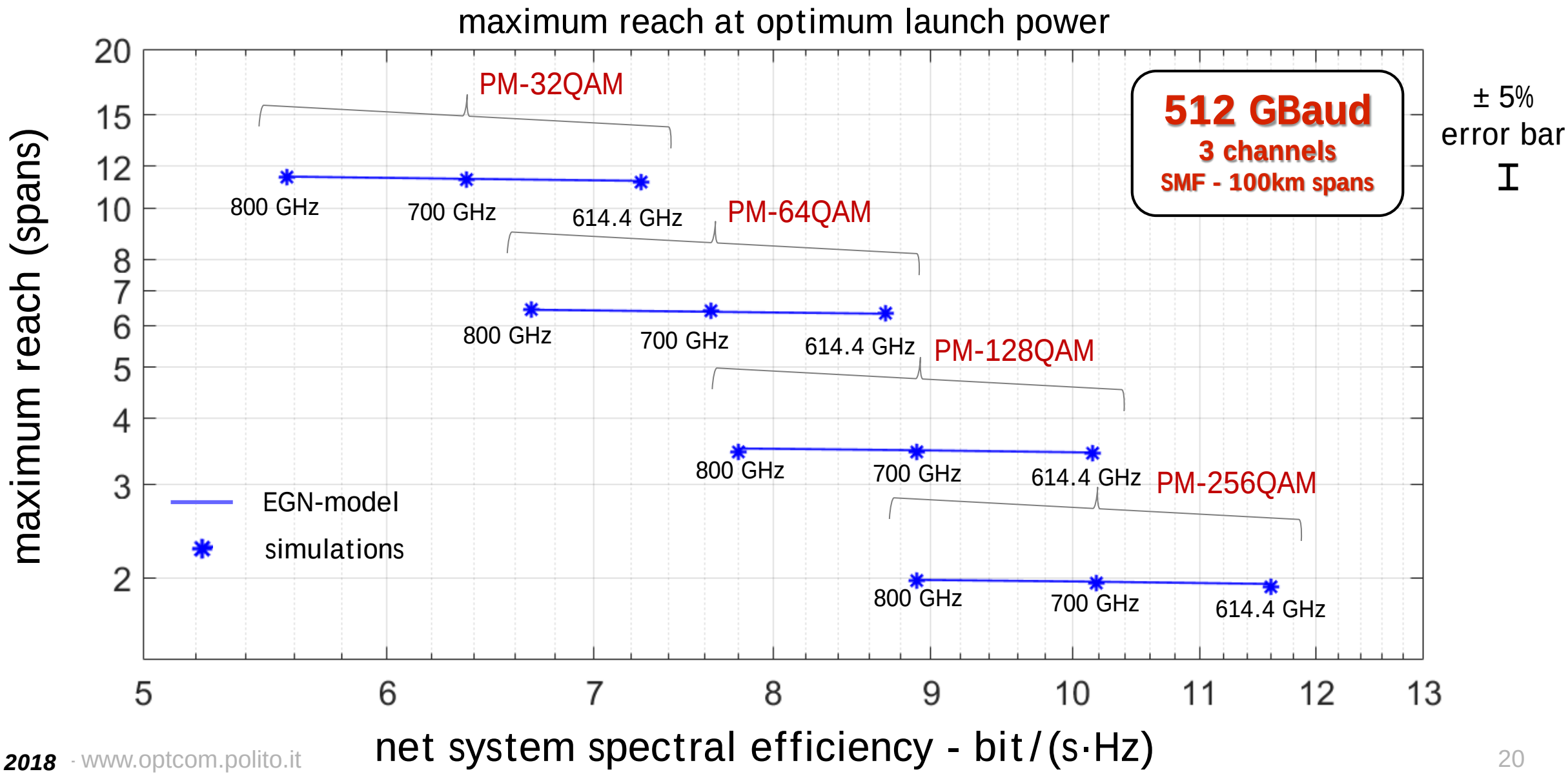
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
800 GHz
700 GHz
614.4 GHz
512 GBaud
3 channels
SMF - 100km spans
± 5%
error bar
EGN-model
simulations
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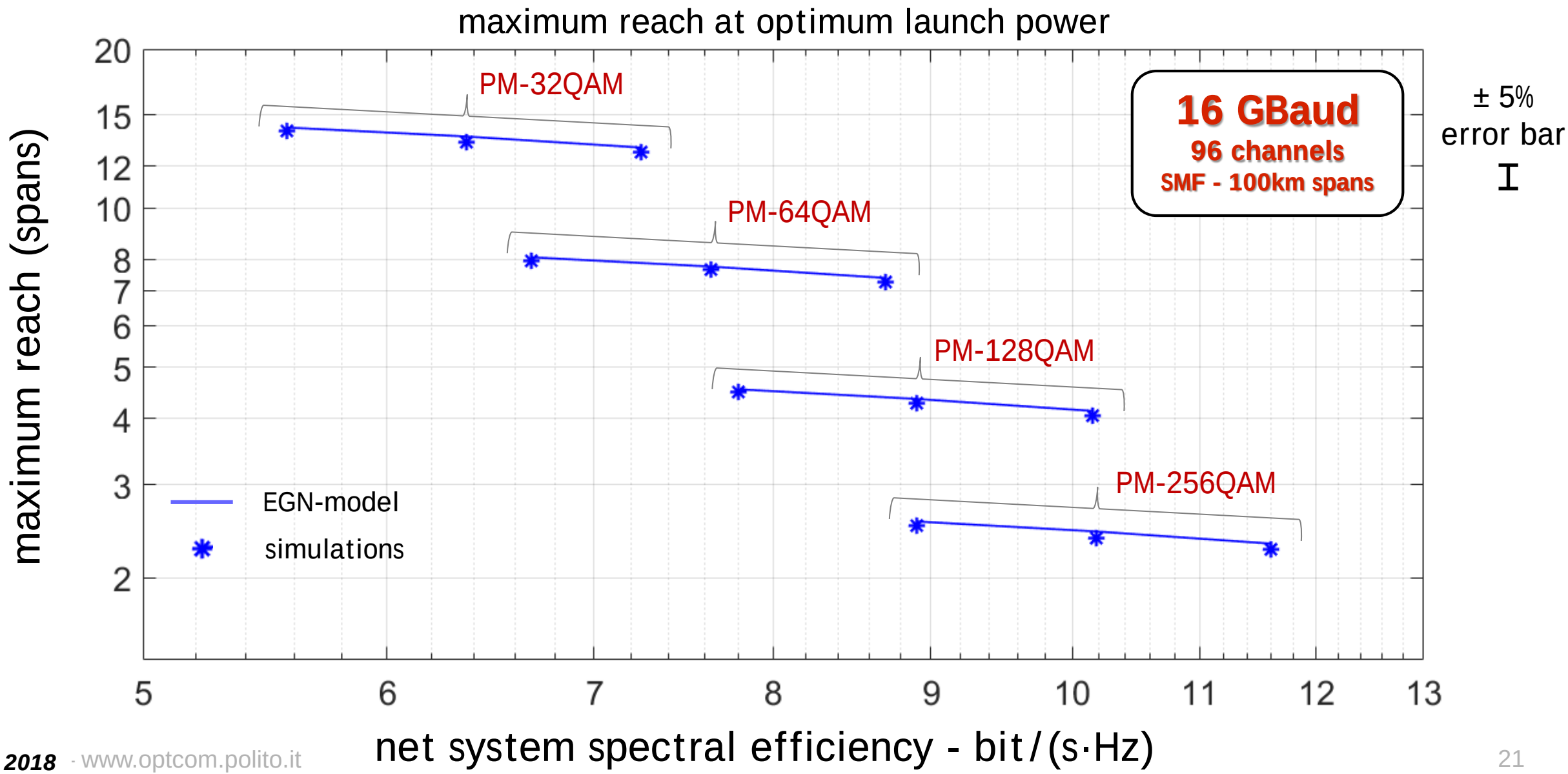
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
16 GBaud
96 channels
SMF - 100km spans
EGN-model
simulations
± 5%
error bar
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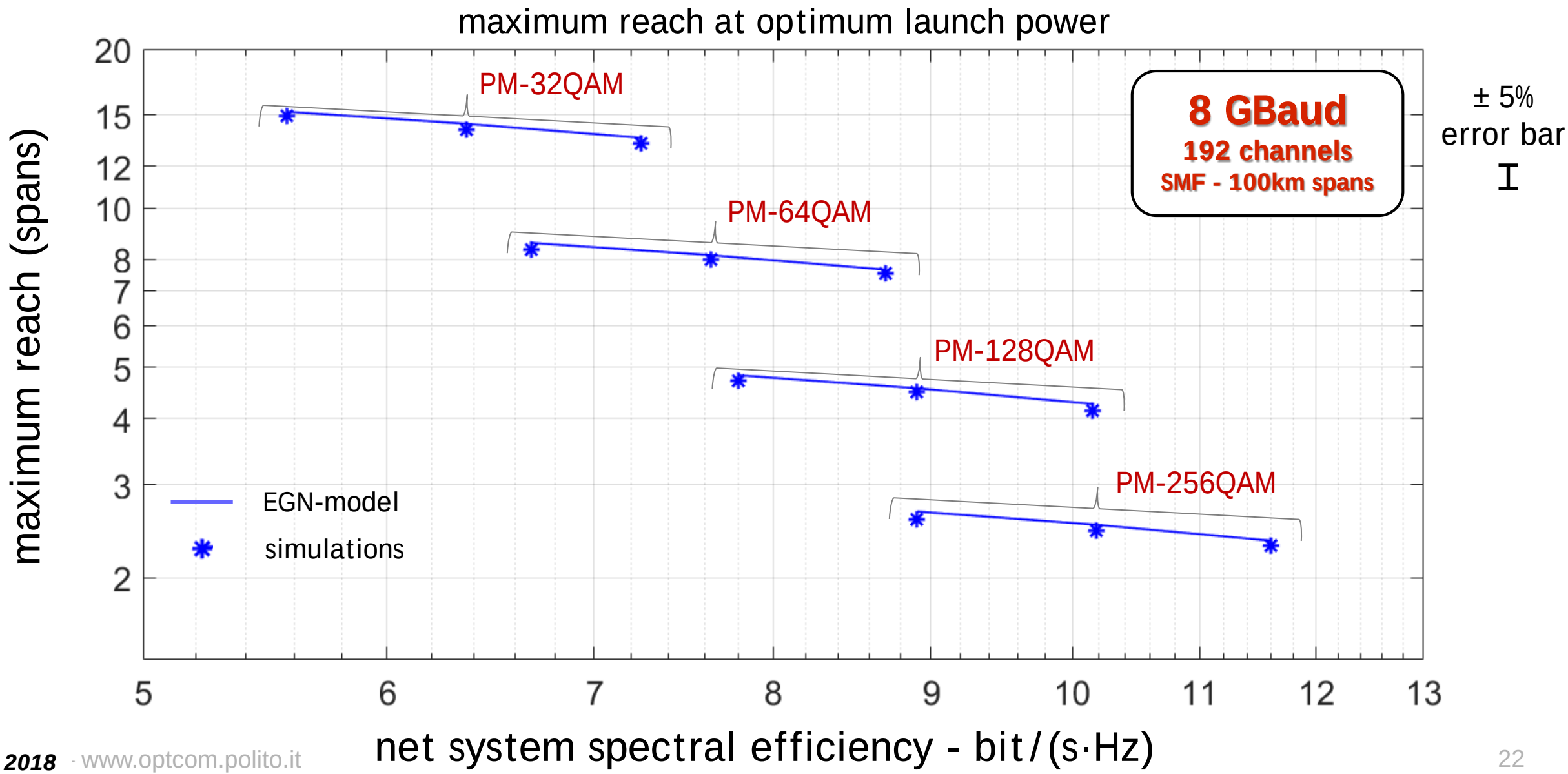

maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
EGN-model
simulations
8 GBaud
192 channels
SMF - 100km spans
± 5%
error bar

- the **EGN-model** is **very accurate across any conceivable symbol rate**
- also (not shown) at low dispersion (D=2) and with shorter spans (60 km)
- using either GMI or pre-FEC BER as performance parameter

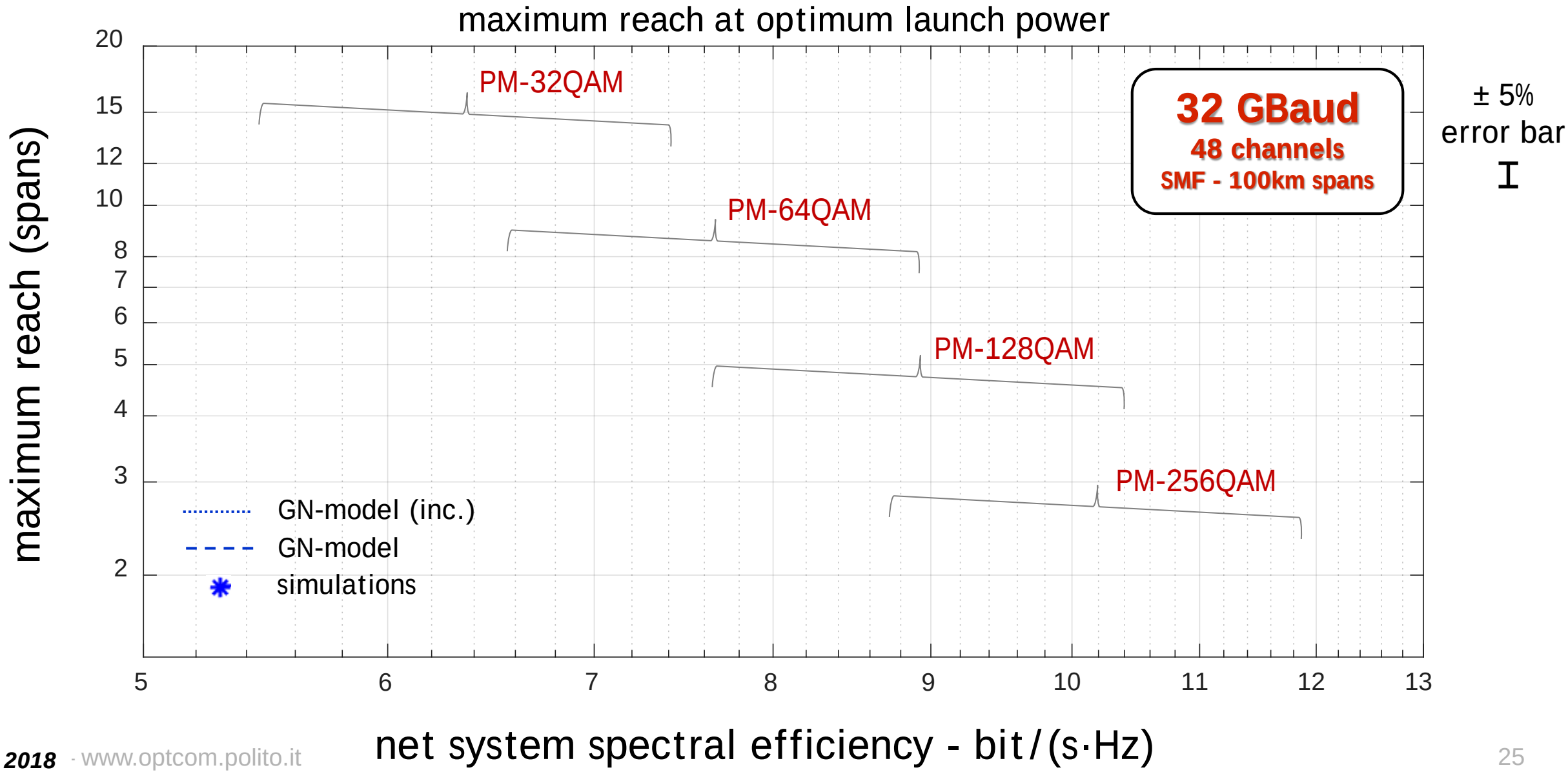
what about the GN model?

- The EGN-model has very good accuracy but it is quite complex
- Other very accurate models exist, but they are *also* very complex

- In many contexts the much simpler GN-model is used because of its simplicity
  - especially in its simplest form: *the incoherent GN-model* (or iGN-model)

- At 32 GBaud the GN-model is 'pessimistic'
  - → it typically underestimates max reach by 5%-10% (long systems) to 15%-20% (short systems)

- *What happens to the GN/iGN models when going up in symbol rate?*


maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
32 GBaud
48 channels
SMF - 100km spans
± 5%
error bar
GN-model (inc.)
GN-model
simulations
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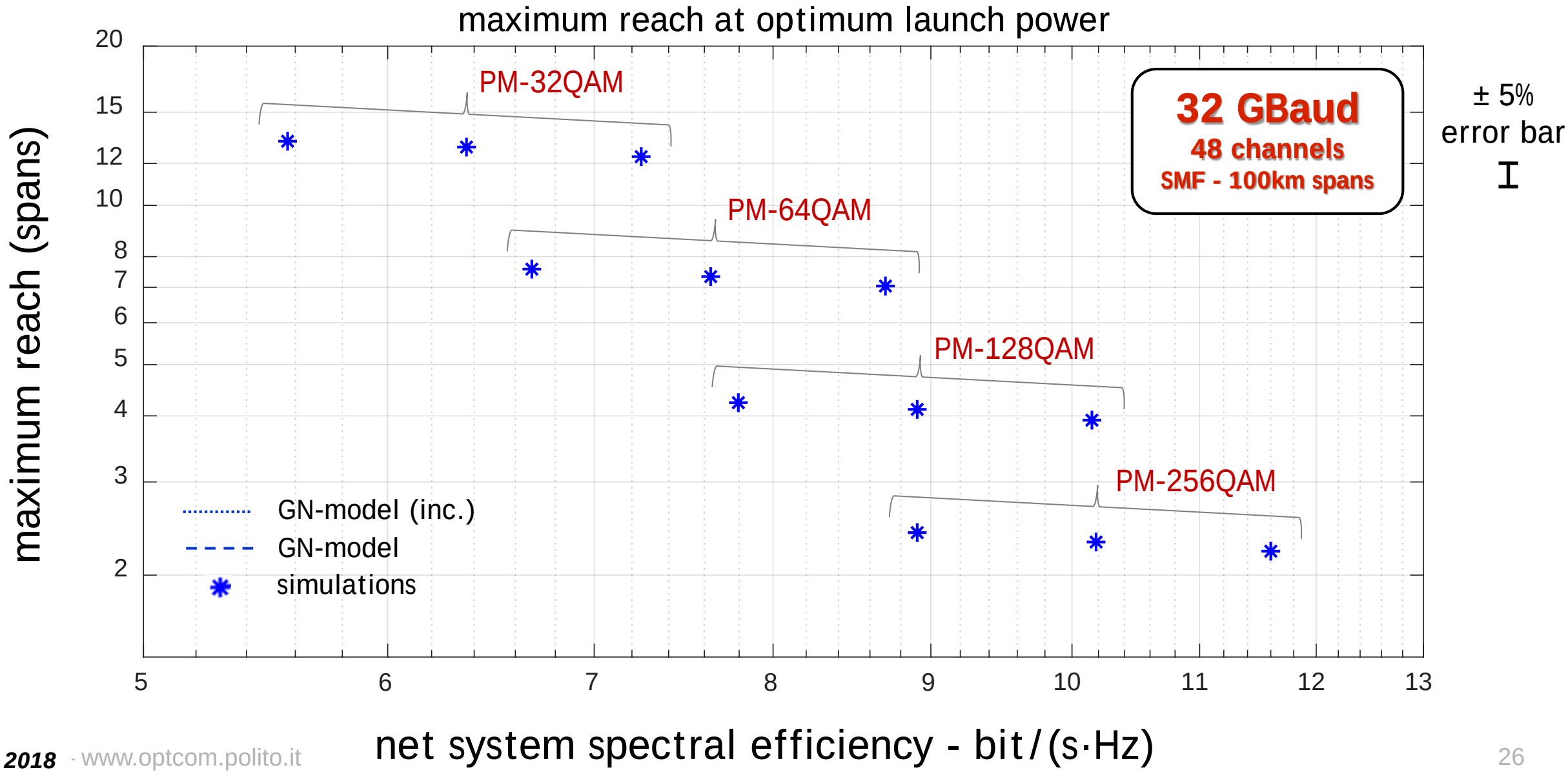
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
32 GBaud
48 channels
SMF - 100km spans
± 5%
error bar
GN-model (inc.)
GN-model
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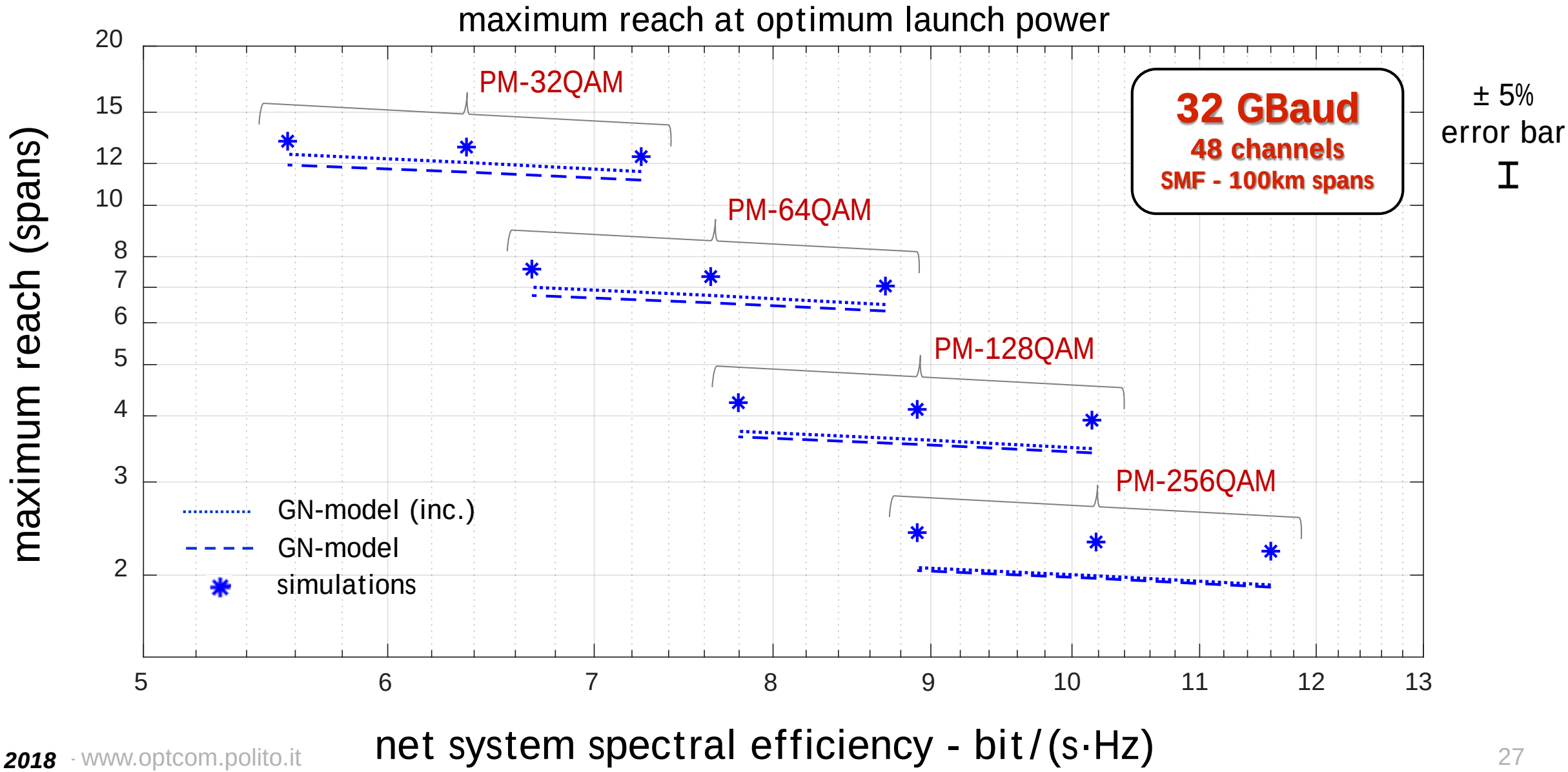
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
32 GBaud
48 channels
SMF - 100km spans
± 5%
error bar
GN-model (inc.)
GN-model
simulations
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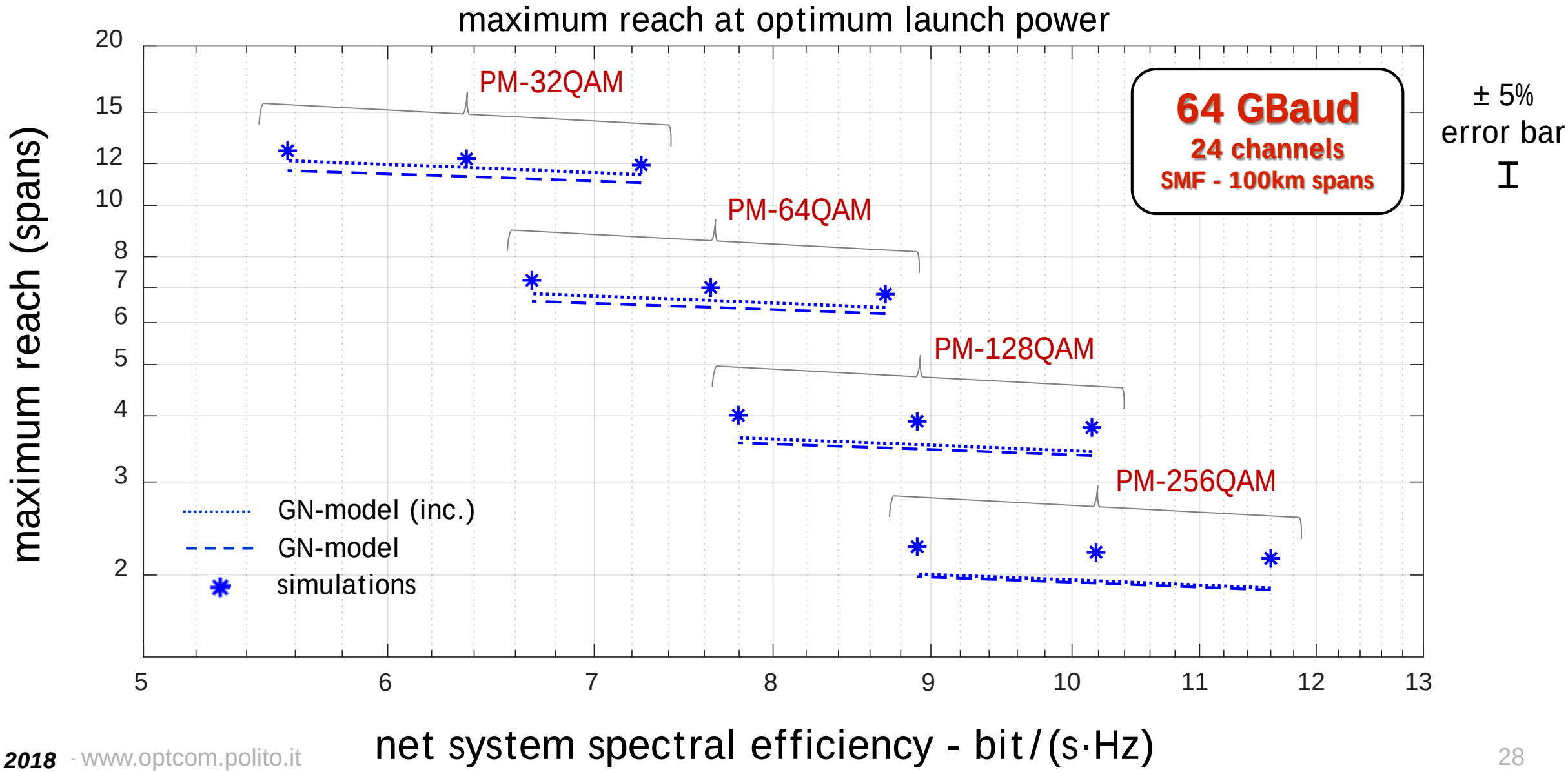
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
64 GBaud
24 channels
SMF - 100km spans
± 5%
error bar
GN-model (inc.)
GN-model
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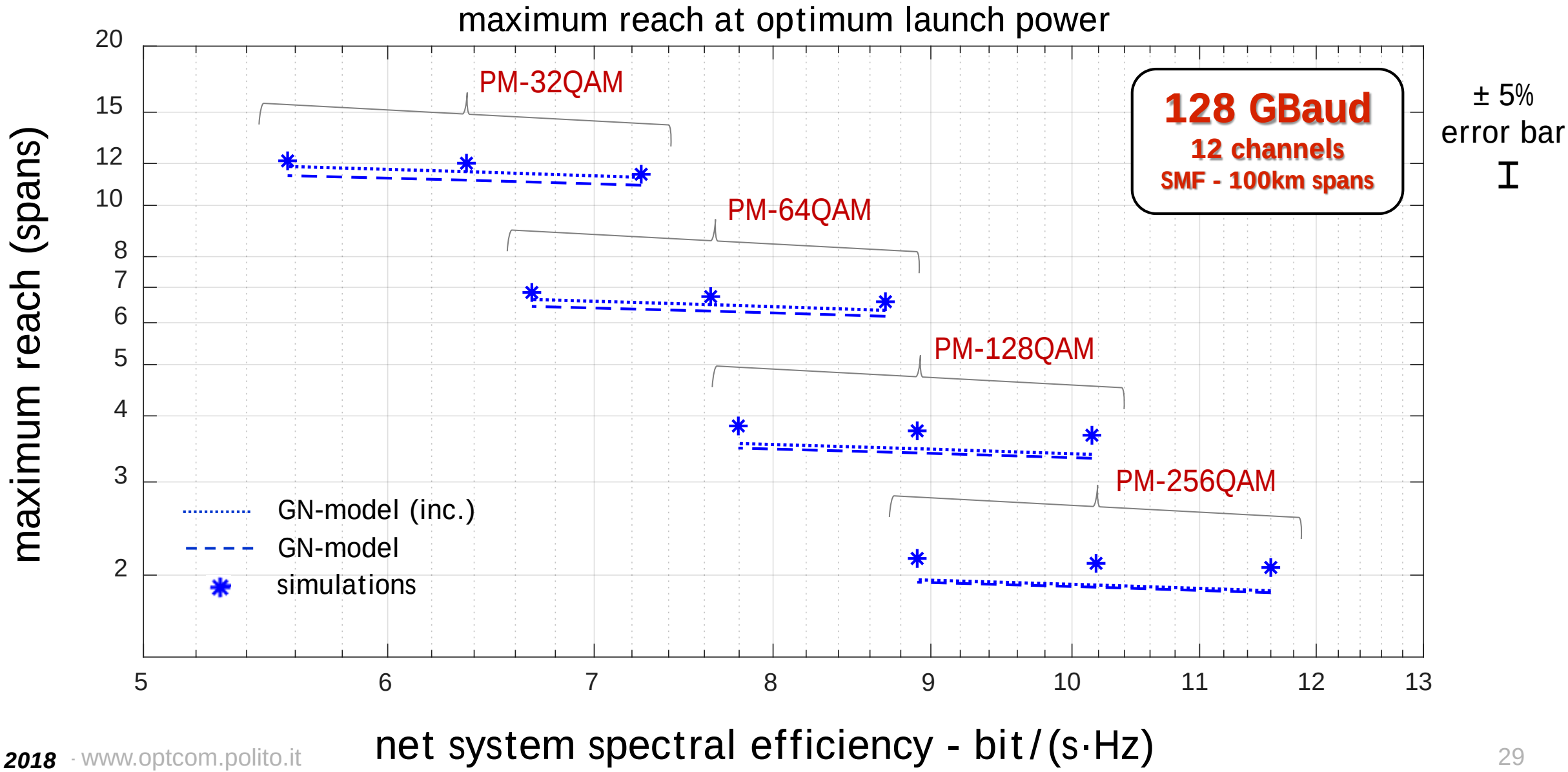
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
128 GBaud
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SMF - 100km spans
± 5%
error bar
GN-model (inc.)
GN-model
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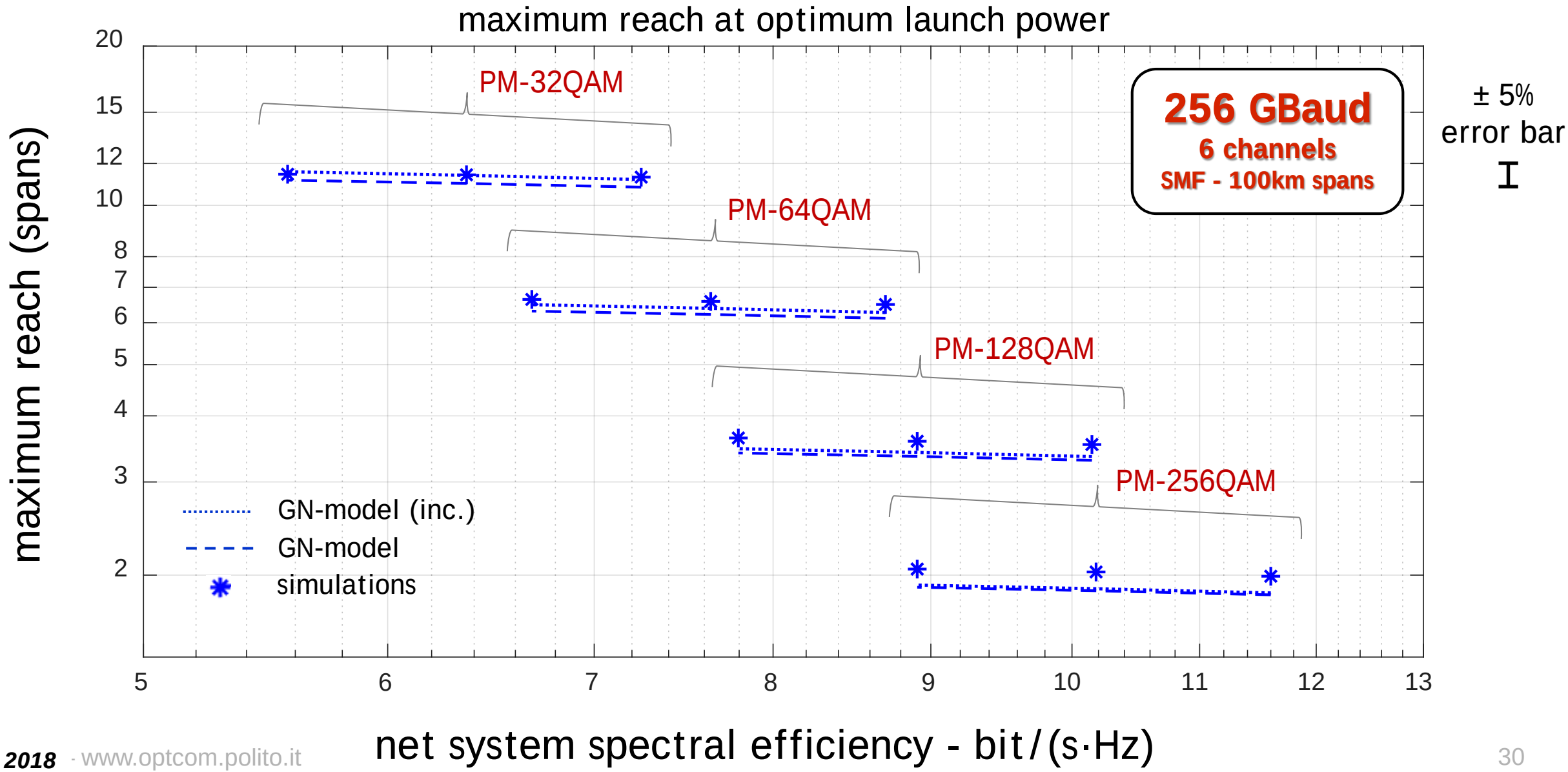
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
256 GBaud
6 channels
SMF - 100km spans
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error bar
GN-model (inc.)
GN-model
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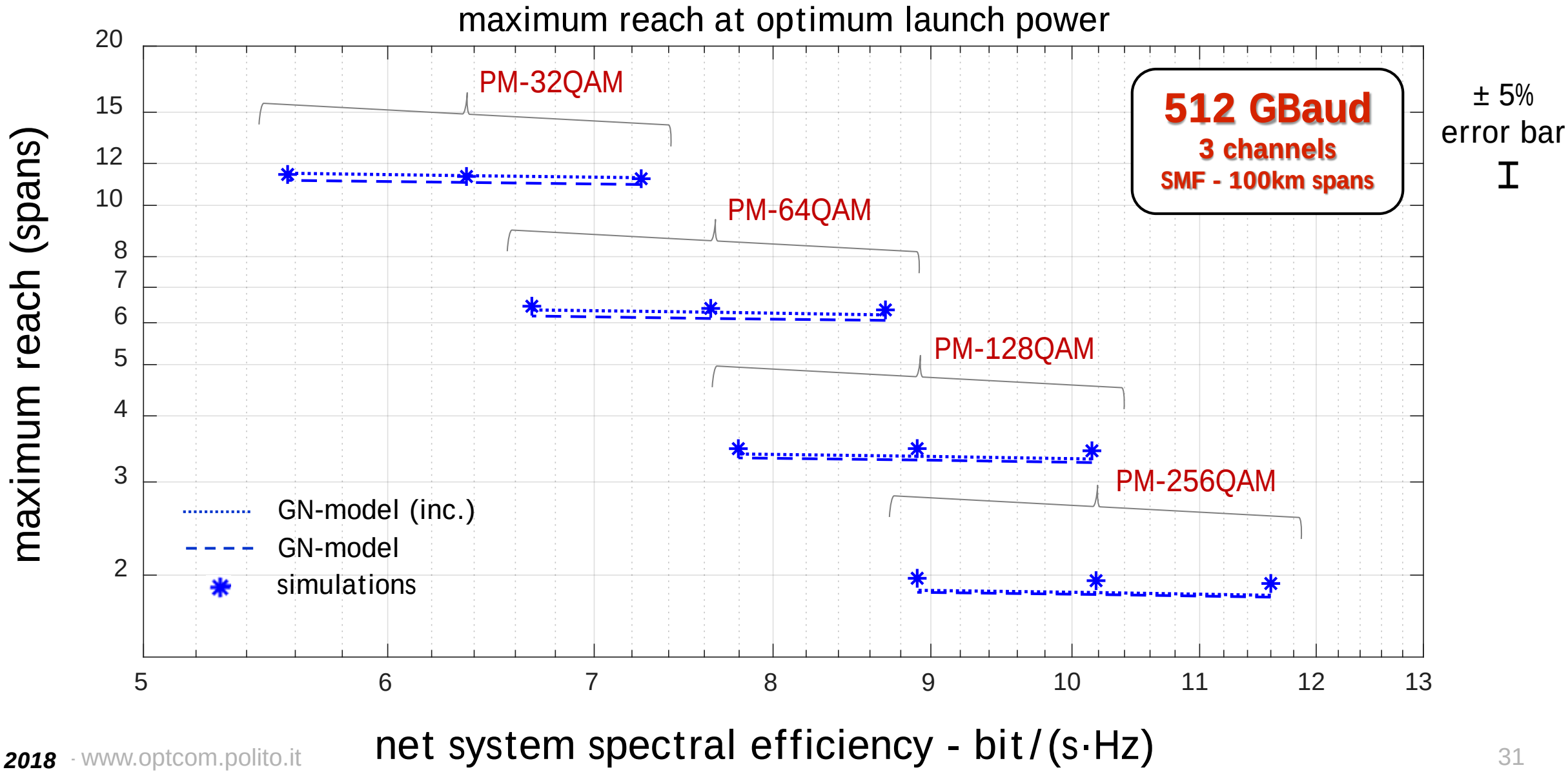
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
512 GBaud
3 channels
SMF - 100km spans
± 5%
error bar
GN-model (inc.)
GN-model
simulations
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Key take-away

- As symbol rates go up **the GN-model gets increasingly more accurate**
- The GN and iGN models *tend to converge*

http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

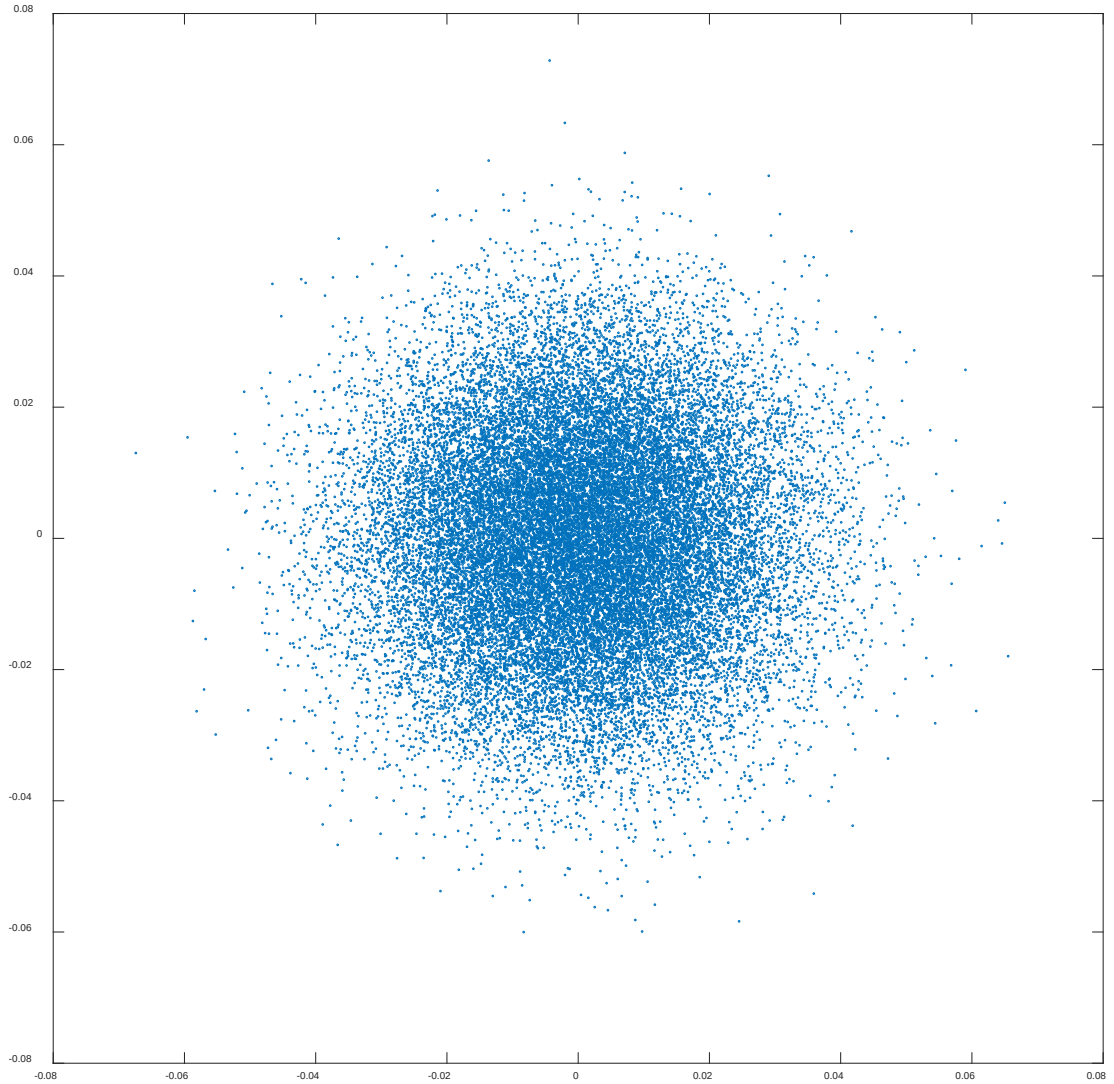
Gaussian constellations

- What happens if the constellation is Gaussian?
- When *ideal Gaussian constellations* are used:

GN model = EGN model

- Do we still get EGN-like good accuracy?
- What happens at ultra-high symbol rates?

Simulated ‘ideal Gaussian’ constellation

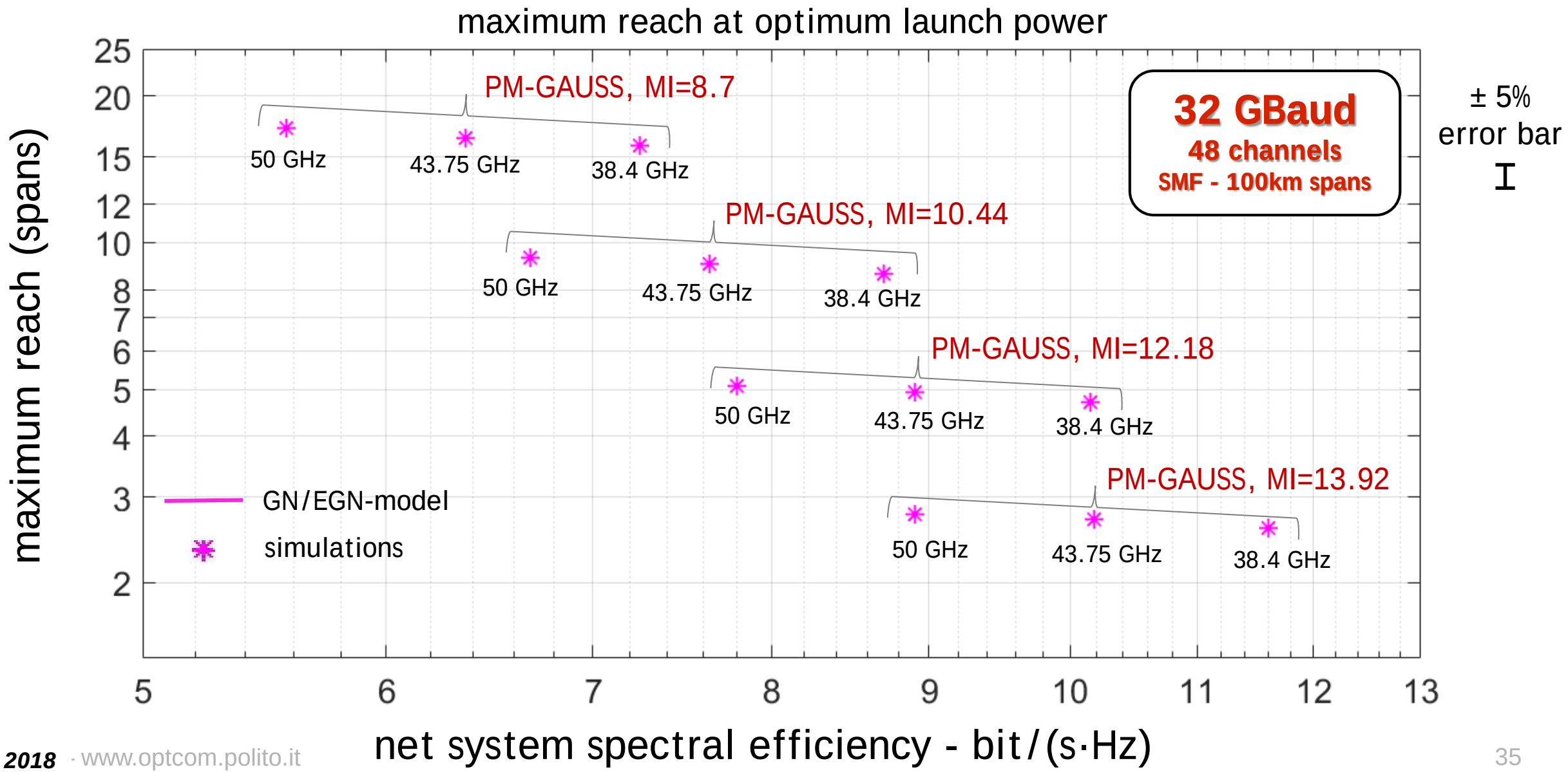


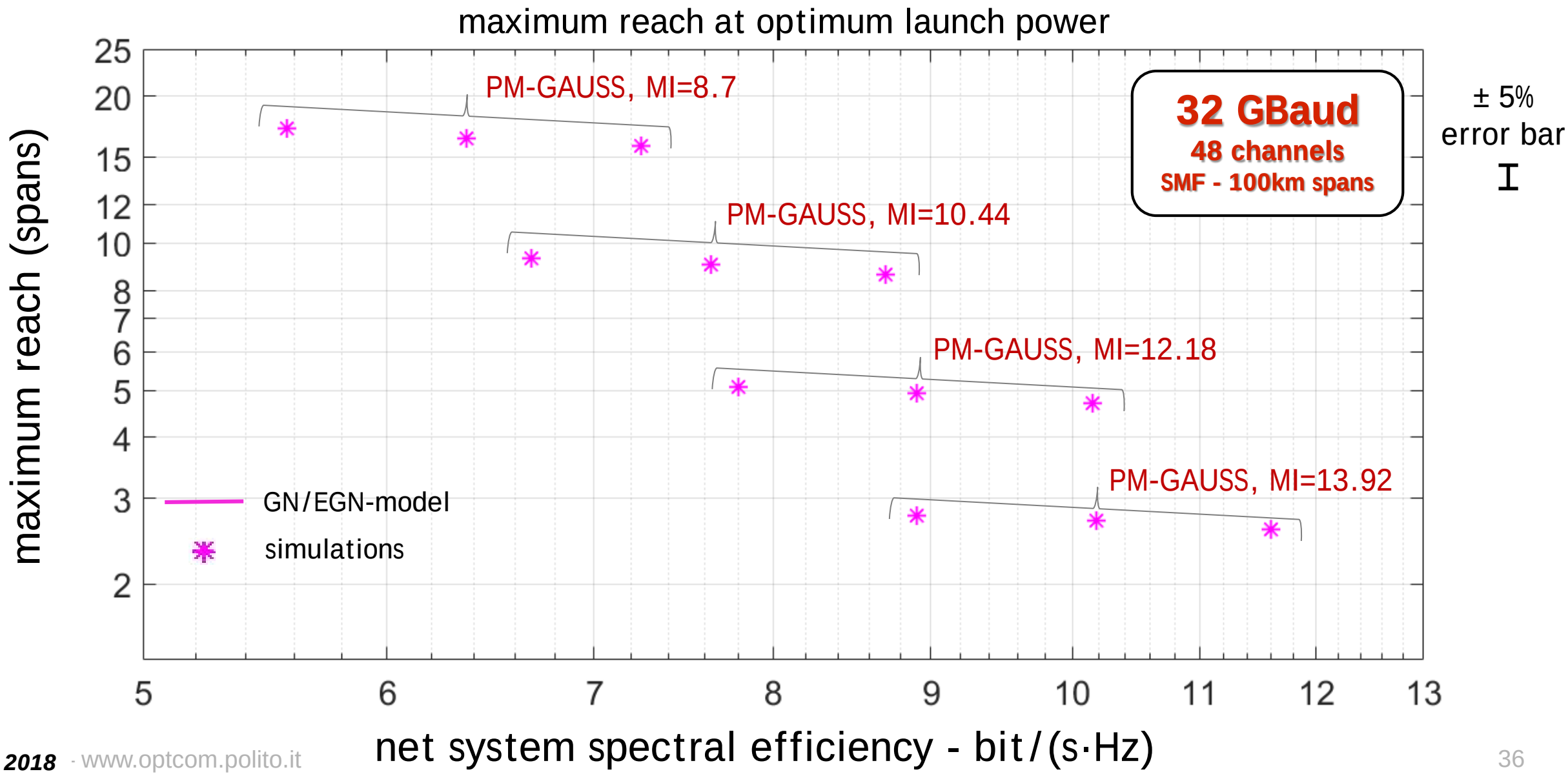
We used an ‘ideal’ Gaussian constellation

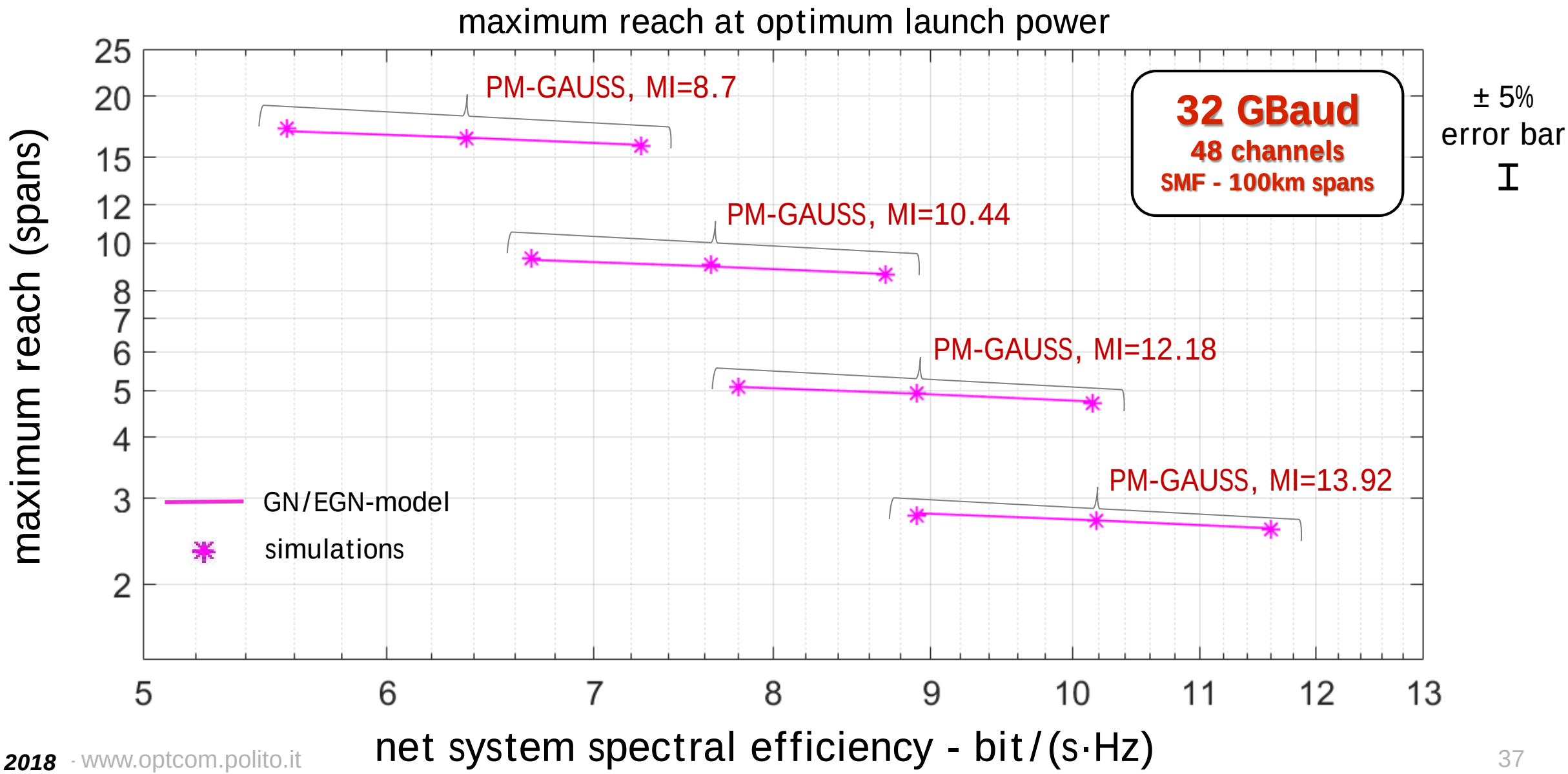
2^{15} Gaussian-distributed constellation points (one polarization)

Entropy is therefore 30 bits/symb over two polarizations

We used MI for performance assessment


maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-GAUSS, MI=8.7
50 GHz
43.75 GHz
38.4 GHz
PM-GAUSS, MI=10.44
50 GHz
43.75 GHz
38.4 GHz
PM-GAUSS, MI=12.18
50 GHz
43.75 GHz
38.4 GHz
PM-GAUSS, MI=13.92
50 GHz
43.75 GHz
38.4 GHz
GN/EGN-model
simulations
32 GBaud
48 channels
SMF - 100km spans
± 5%
error bar


maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-GAUSS, MI=8.7
PM-GAUSS, MI=10.44
PM-GAUSS, MI=12.18
PM-GAUSS, MI=13.92
32 GBaud
48 channels
SMF - 100km spans
GN/EGN-model
simulations
± 5%
error bar


maximum reach at optimum launch power
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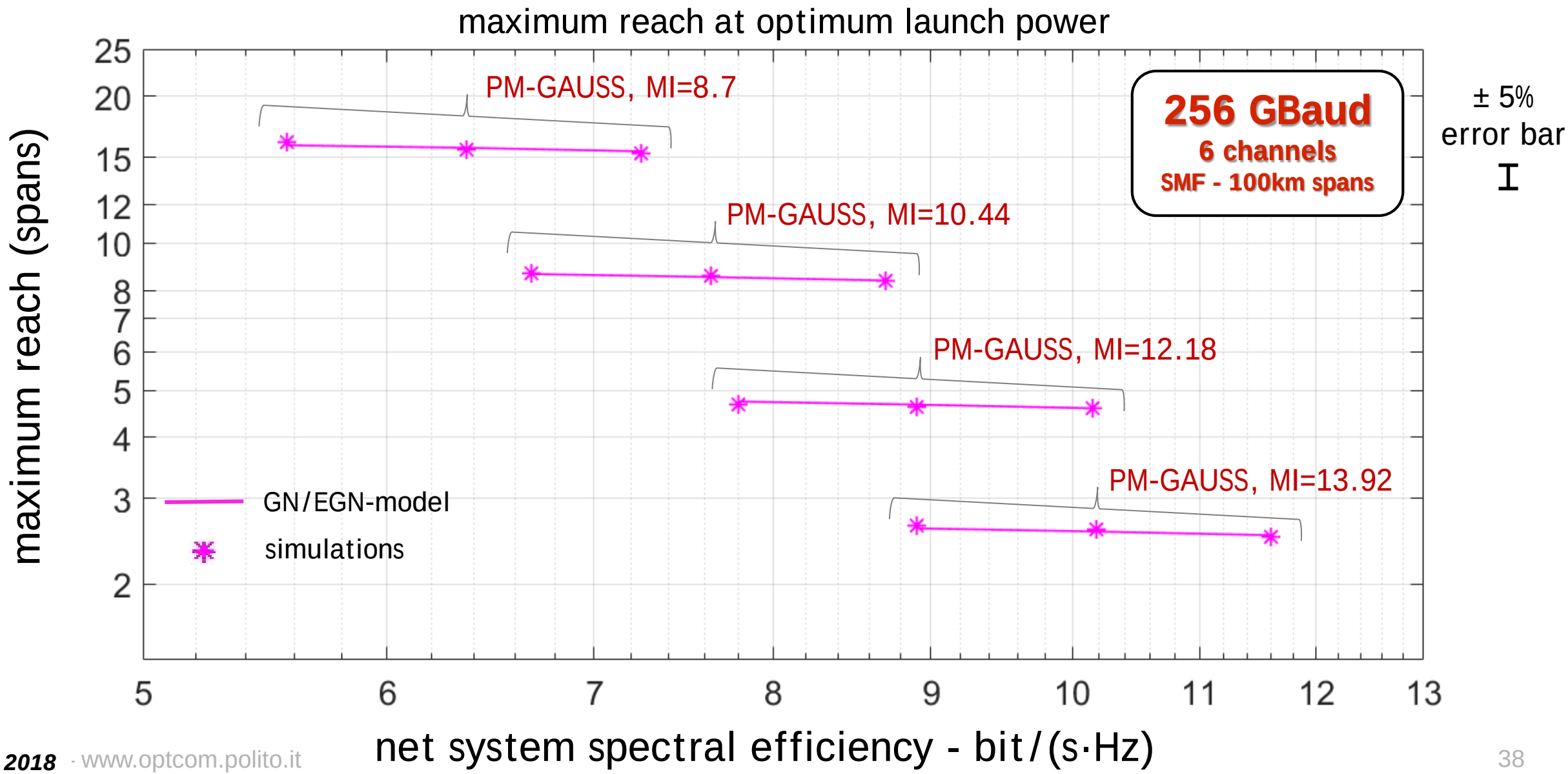
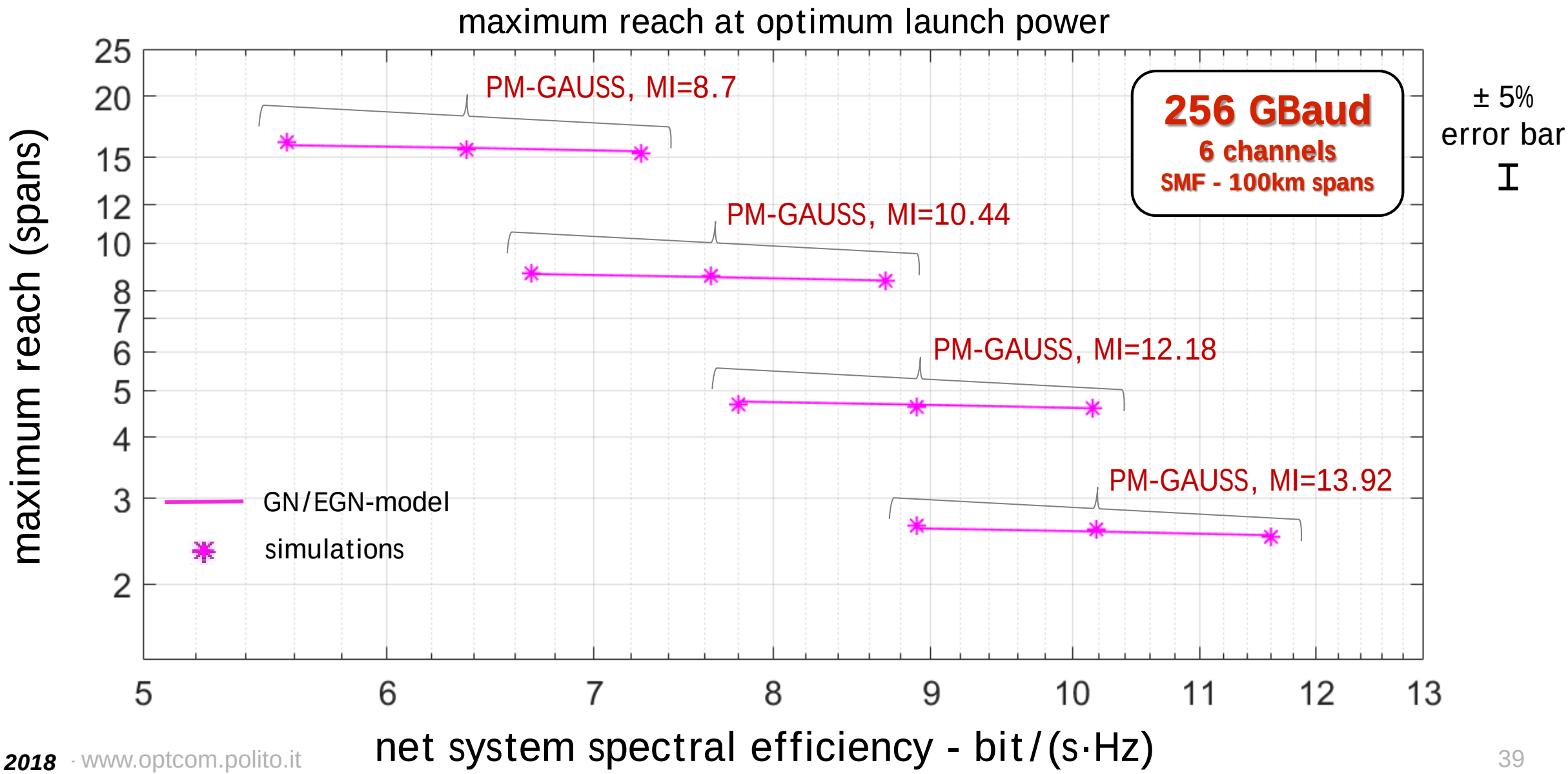
GN/EGN-model
simulations
± 5%
error bar


maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-GAUSS, MI=8.7
PM-GAUSS, MI=10.44
PM-GAUSS, MI=12.18
PM-GAUSS, MI=13.92
256 GBaud
6 channels
SMF - 100km spans
GN/EGN-model
simulations
± 5%
error bar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256 GBaud
6 channels
SMF - 100km spans
GN/EGN-model
simulations
± 5%
error bar

Key take-away

- For **Gaussian constellations**,
  - the GN-model coincides with the EGN-model
  - accuracy stays excellent at all rates
  - so we have EGN model accuracy at all rates, with the low complexity of the GN

- In the paper, you can find a discussion of Non-Linear Phase Noise (NLPN)

- A thorough assessment of its impact on modeling was carried out, under certain assumptions

Key take-away

- **Going towards high symbol rates:**
  - NLPN decreases as shown by the models
  - Also, mitigating it gets easier
- As a result, overall, its impact on modeling decreases

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Conclusion

- We explored ultra-high symbol rates, using GMI and both QAM and ideal Gaussian constellations

- We found:
  - The EGN-model is always very accurate
  - The GN-model improves its accuracy going up in rate
  - For Gaussian constellations GN and EGN coincide and accuracy is very good
  - Using MI/GMI instead of pre-FEC BER does not impact model accuracy

thank you !

- In general, the good news is that NLI modeling appears to become ***easier*** at larger symbol rates
- large constellations, Gaussian constellations and MI/GMI do not compromise accuracy

This presentation available from tomorrow at: www.optcom.polito.it/talks