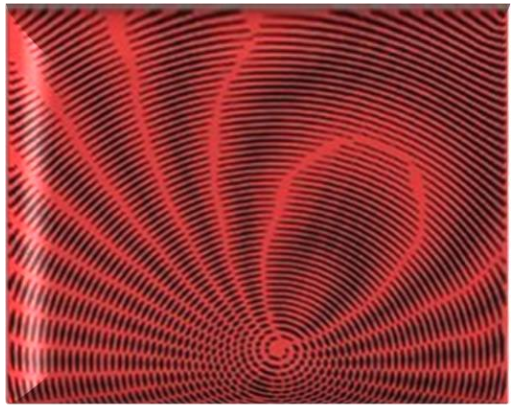
OPTCOM

Non-linearity Modeling at Ultra-high Symbol Rates



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Thanks!

- To **CISCO Photonics** for supporting the research
- **Chris Fludger**, **Alberto Tanzi**, **Marco Mazzini** and many others from CISCO Photonics
- To **Mattia Cantono** e **Dario Pilori** for their invaluable help in setting up and tuning the servers and GPUs that made this paper possible
  - now pushing upward of 100 Tflopfs

Context

- 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: 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 the work well, within their range of validity

Trends

- One current strong industry trend is to move swiftly towards higher rates
  - 64 GBaud is here now
  - 96-128 are around the corner
  - 256 ? 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 ?*

What we investigated

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

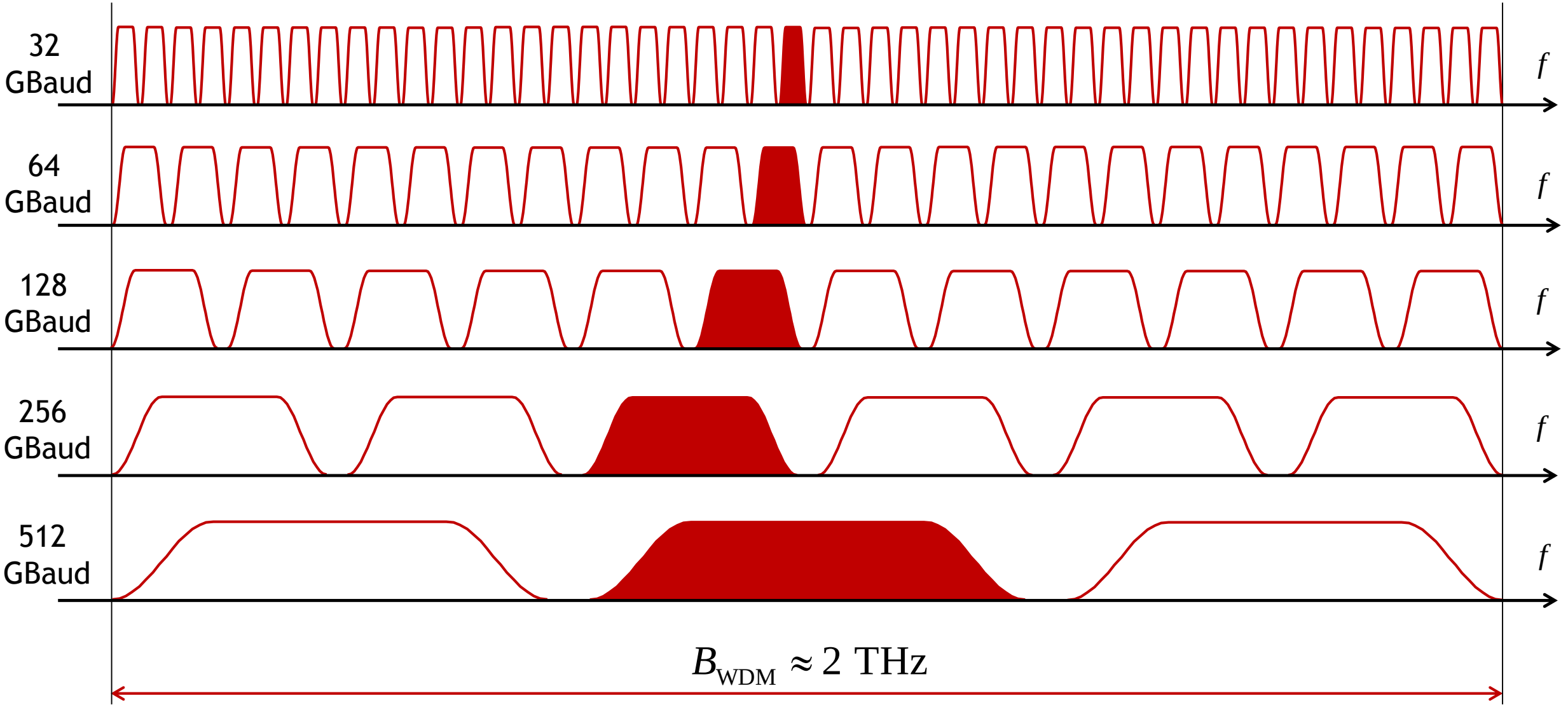
- Specifically, we compared the prediction of System Maximum Reach, obtained using both the GN/EGN models and split-step simulations

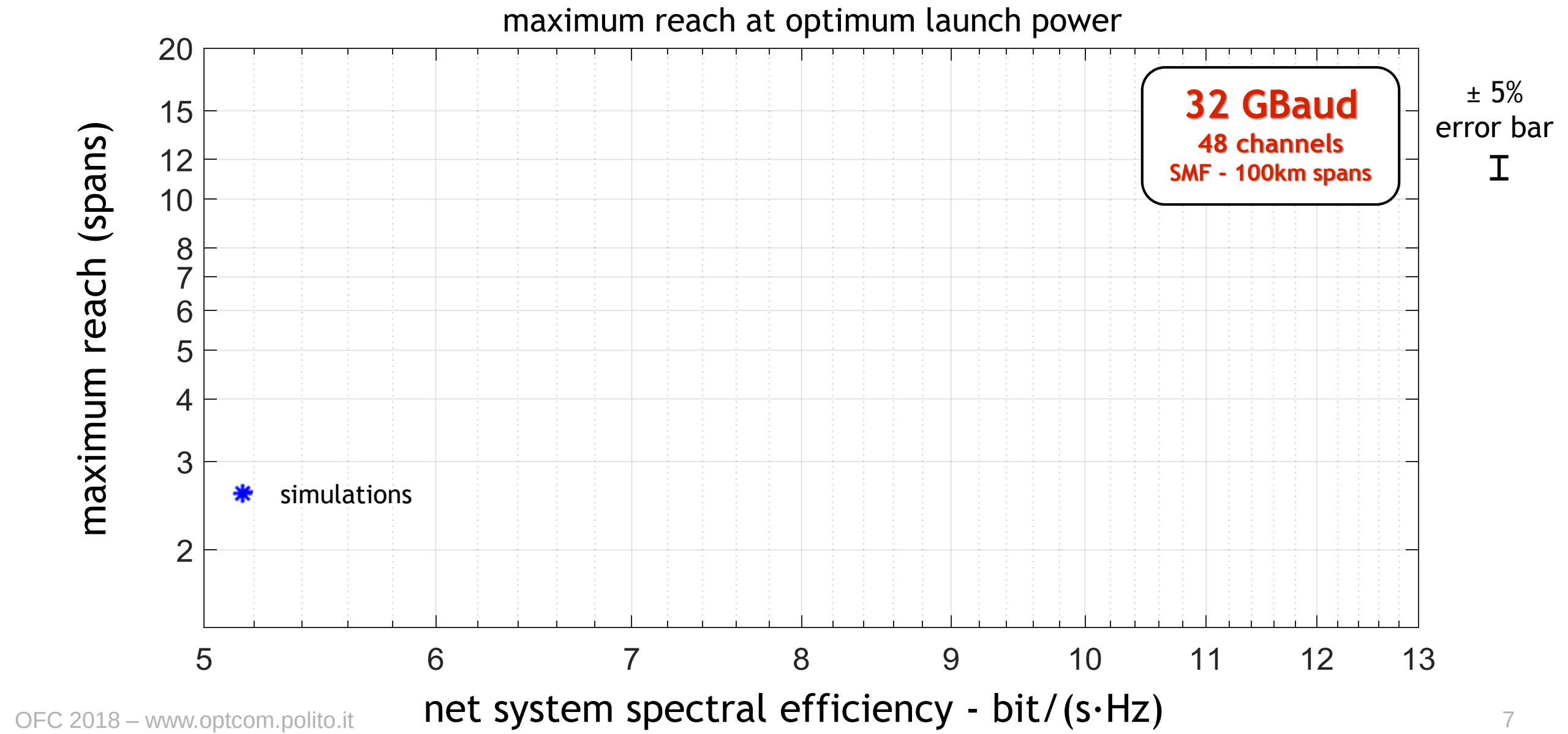
- The maximum reach for a system is achieved when its MI/GMI goes below a set threshold

- For each format the GMI threshold was chosen as 87% of entropy
  - for instance: **PM-32QAM** → 10 x 87% = **8.7 bits/symb**
  - corresponds to **15% coding overhead**

- SMF, 100 km spans, EDFA NF 6dB, roll-off 0.2

very different scenarios…




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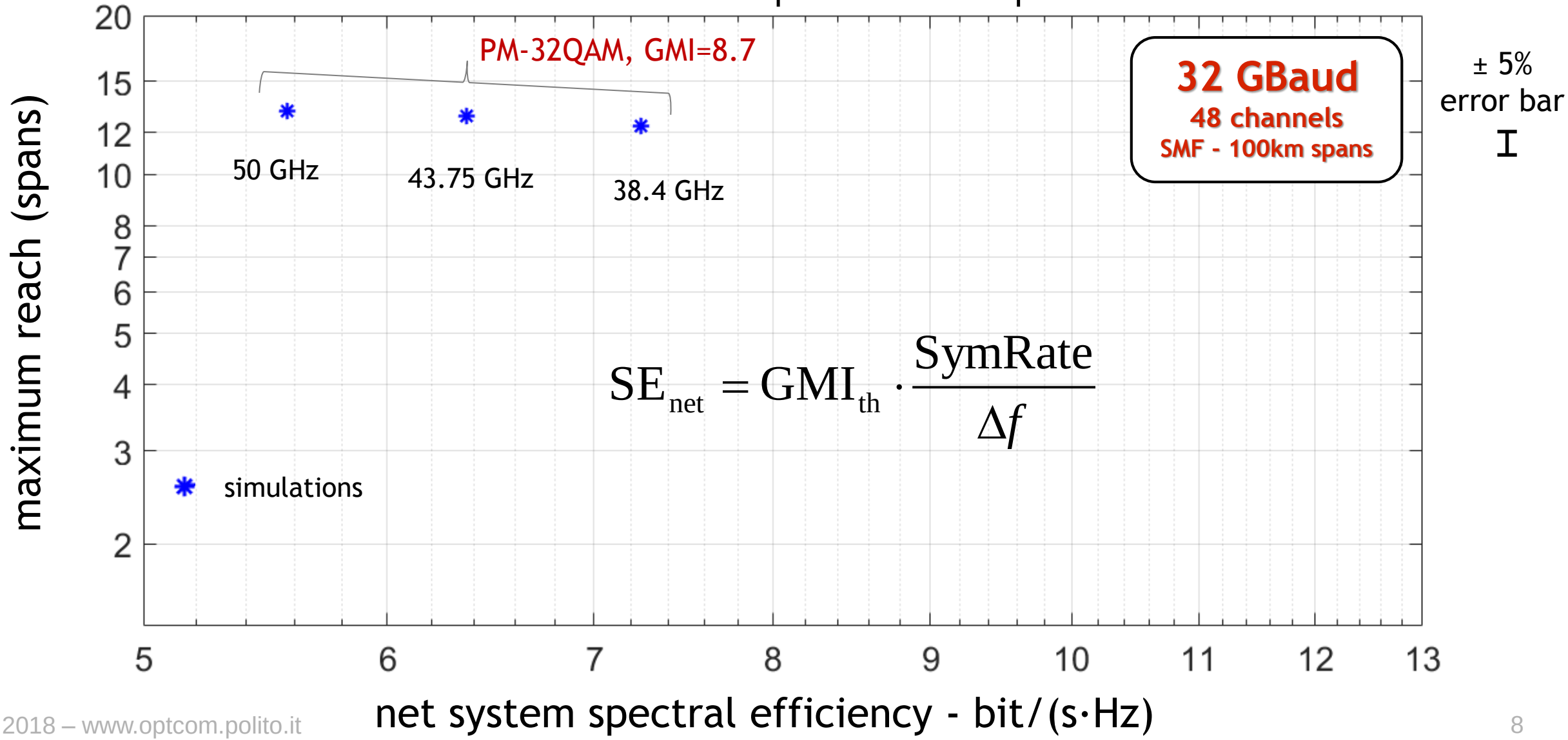
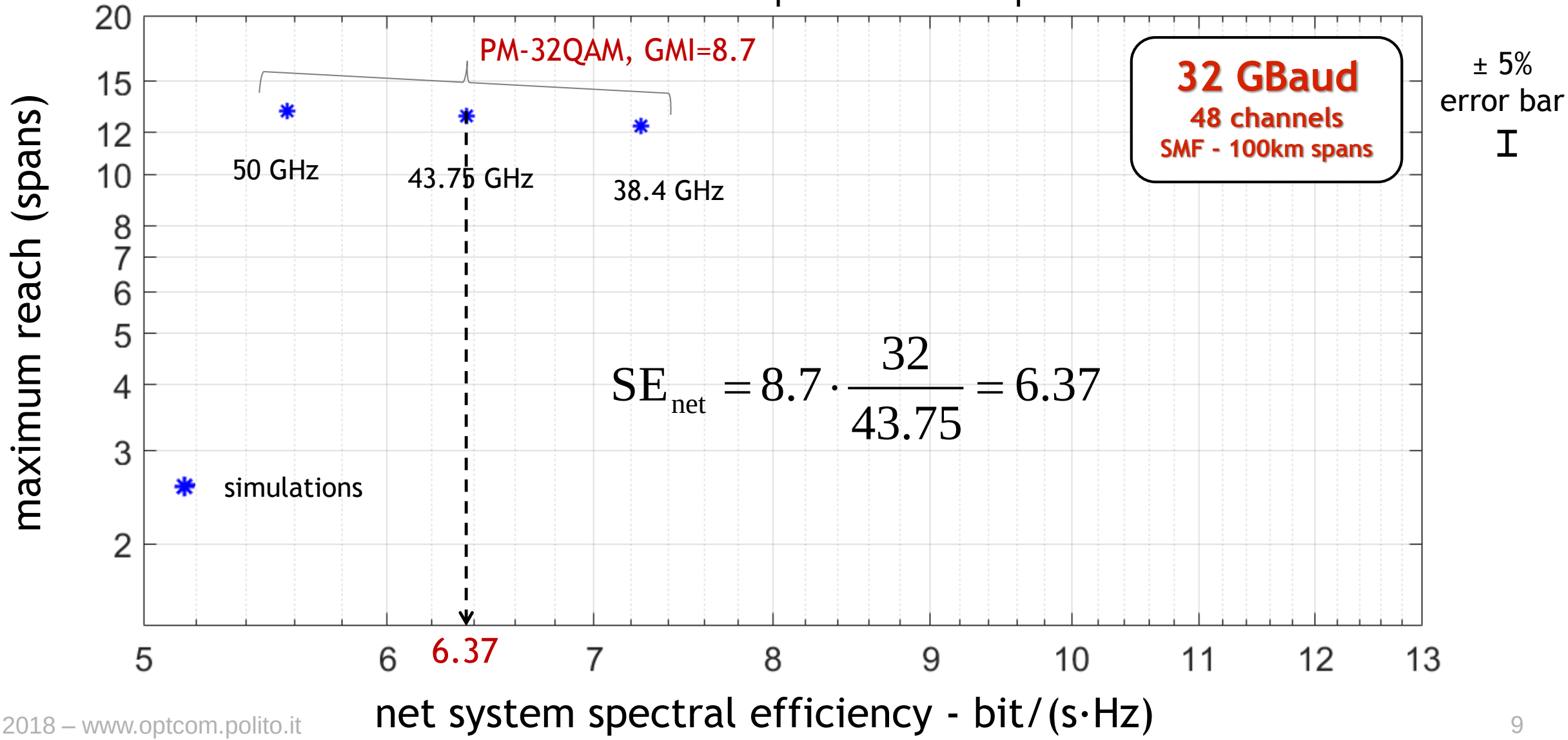
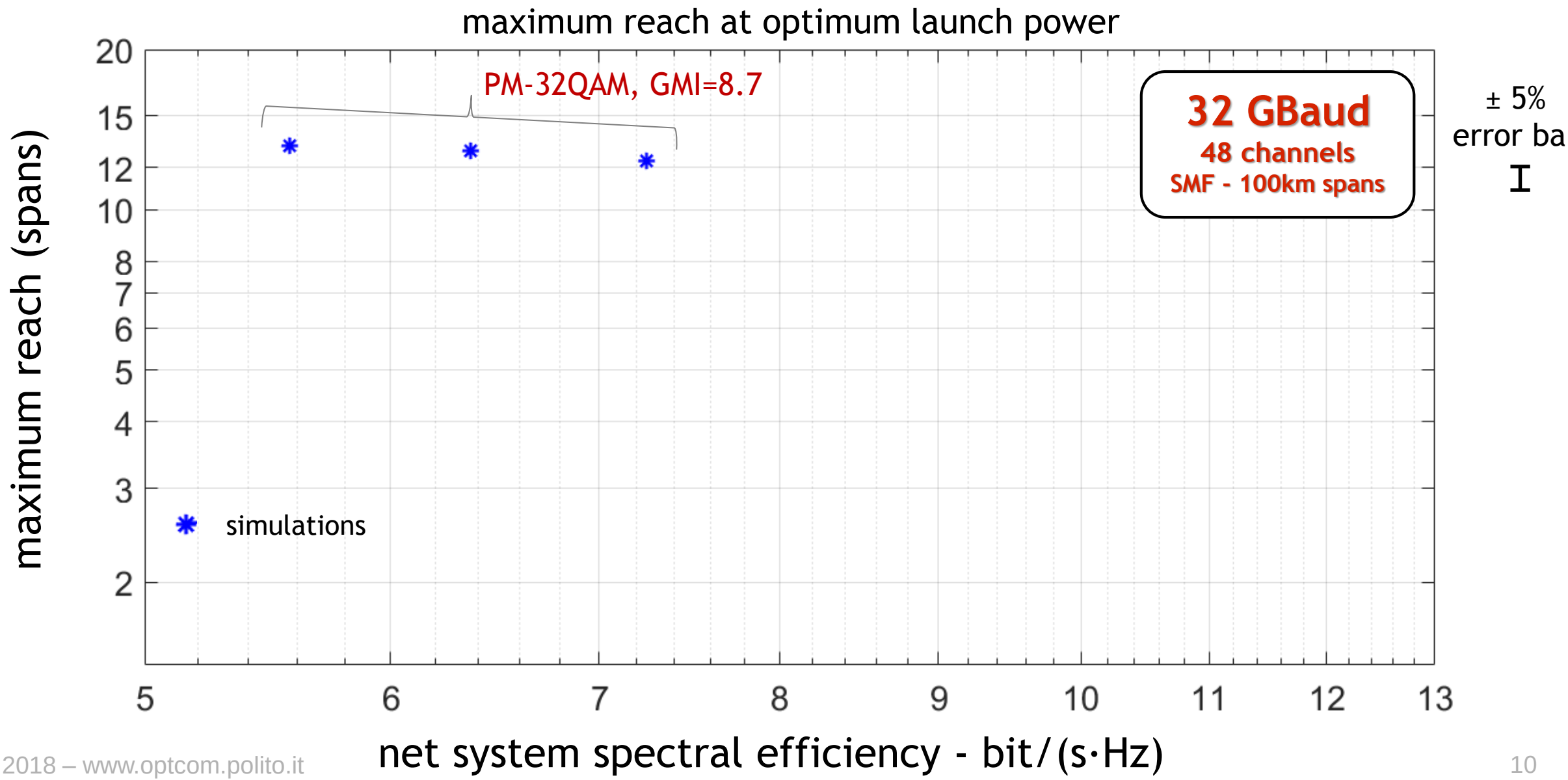
net system spectral efficiency - bit/(s·Hz)

maximum reach at optimum launch power



maximum reach at optimum launch power




maximum reach at optimum launch power
PM-32QAM, GMI=8.7
32 GBaud
48 channels
SMF - 100km spans
± 5%
error bar
simulations
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
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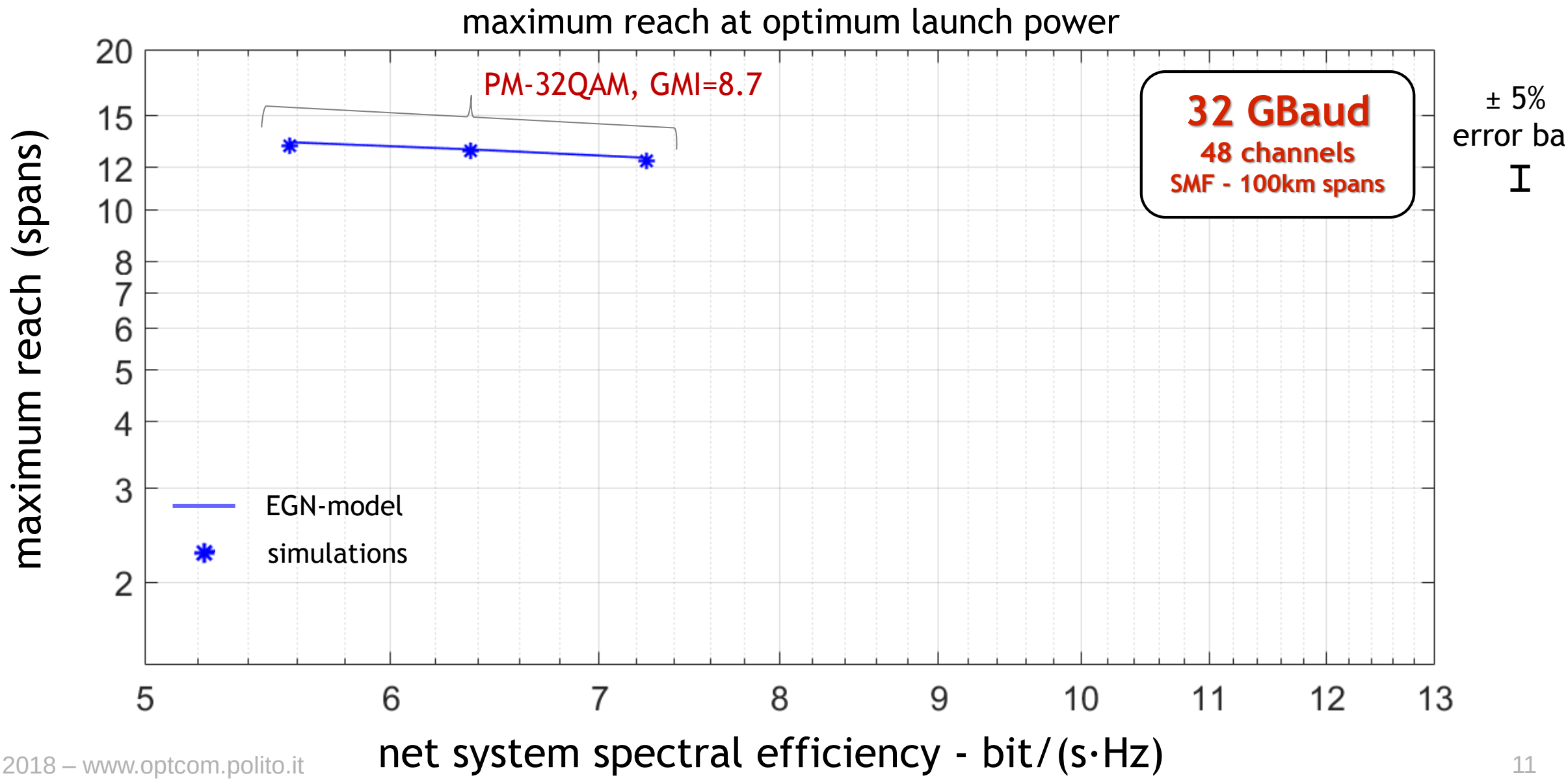
maximum reach at optimum launch power
PM-32QAM, GMI=8.7
32 GBaud
48 channels
SMF - 100km spans
± 5%
error bar
EGN-model
simulations
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
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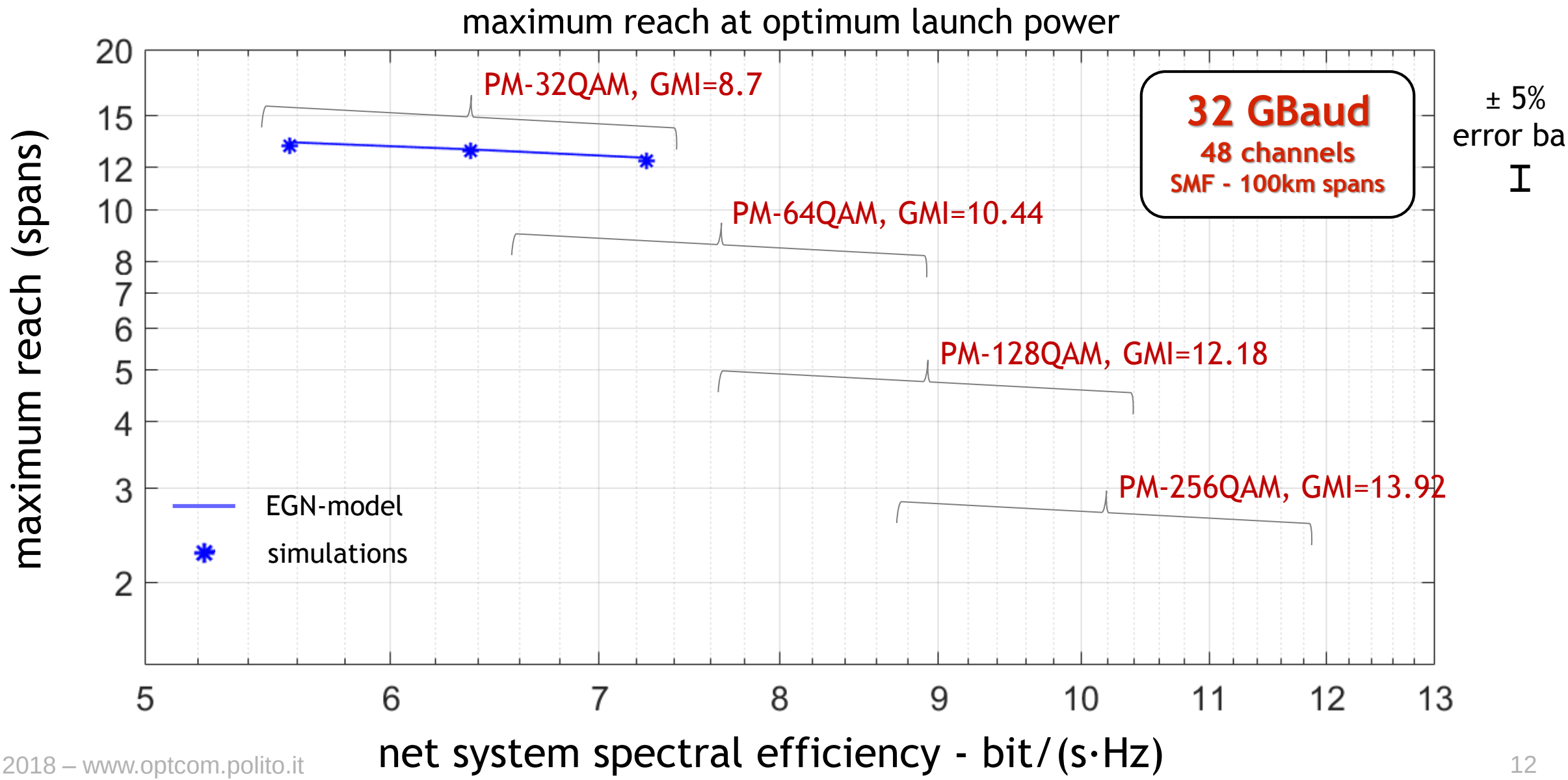
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM, GMI=8.7
PM-64QAM, GMI=10.44
PM-128QAM, GMI=12.18
PM-256QAM, GMI=13.92
32 GBaud
48 channels
SMF - 100km spans
EGN-model
simulations
± 5%
error bar
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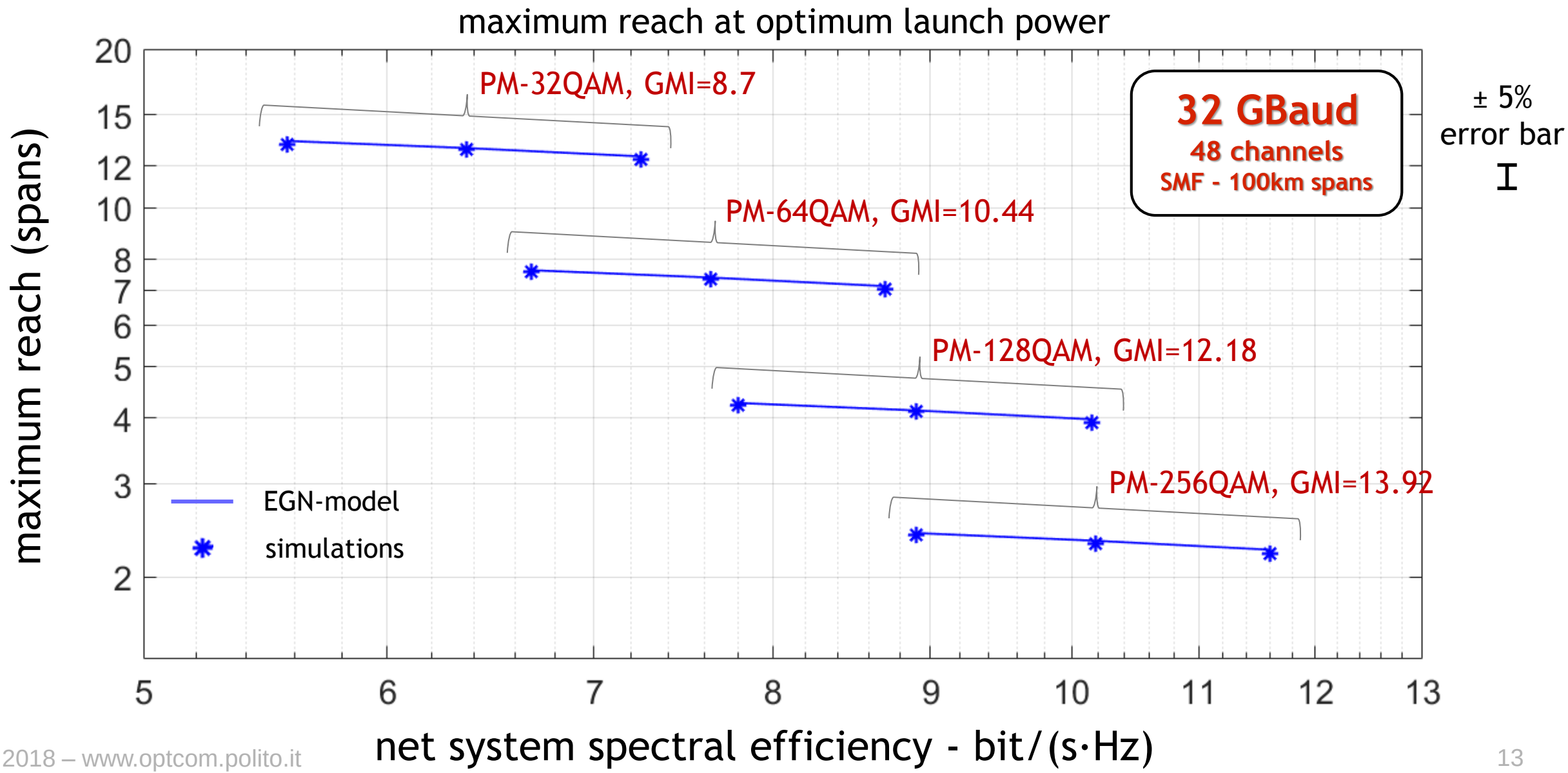
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
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PM-128QAM, GMI=12.18
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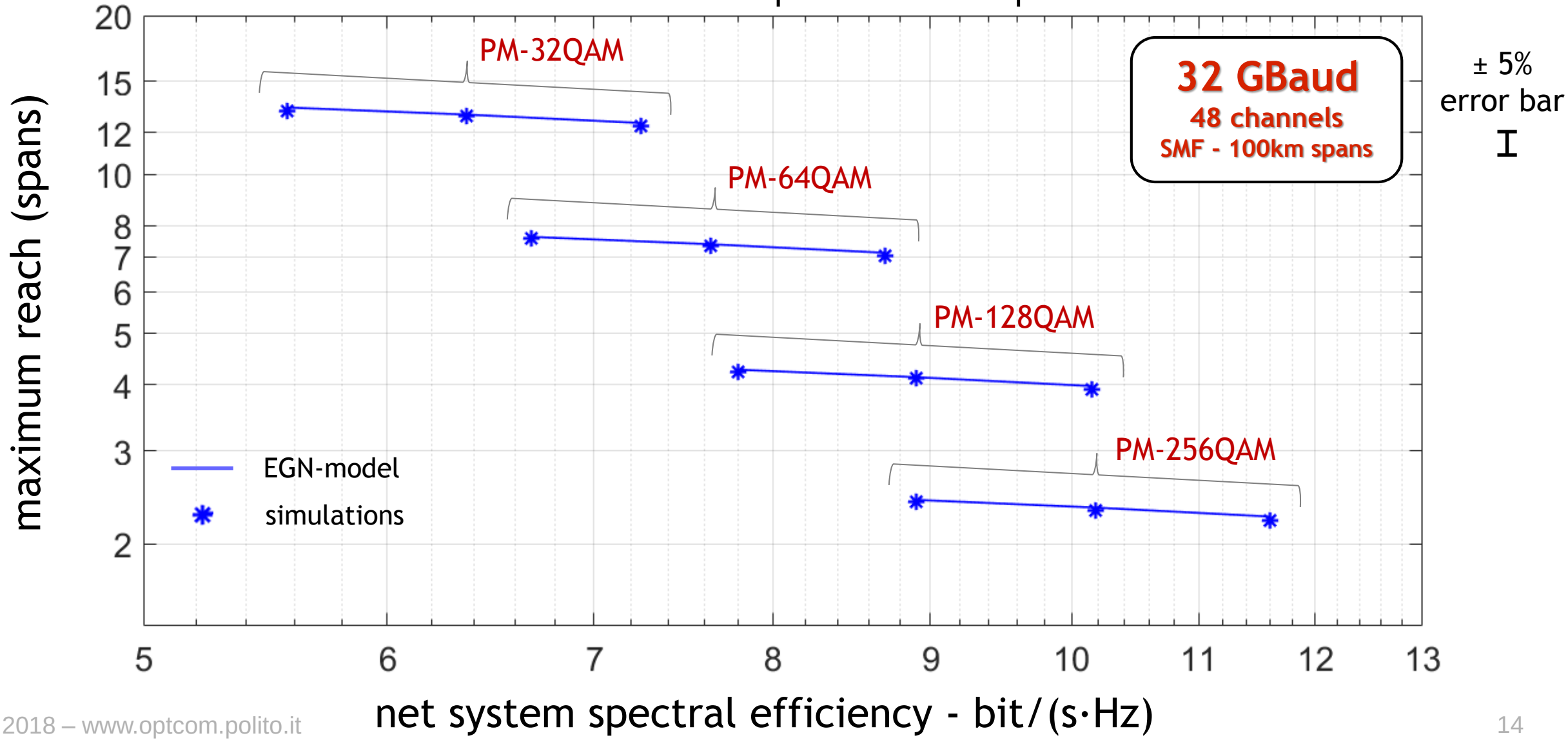
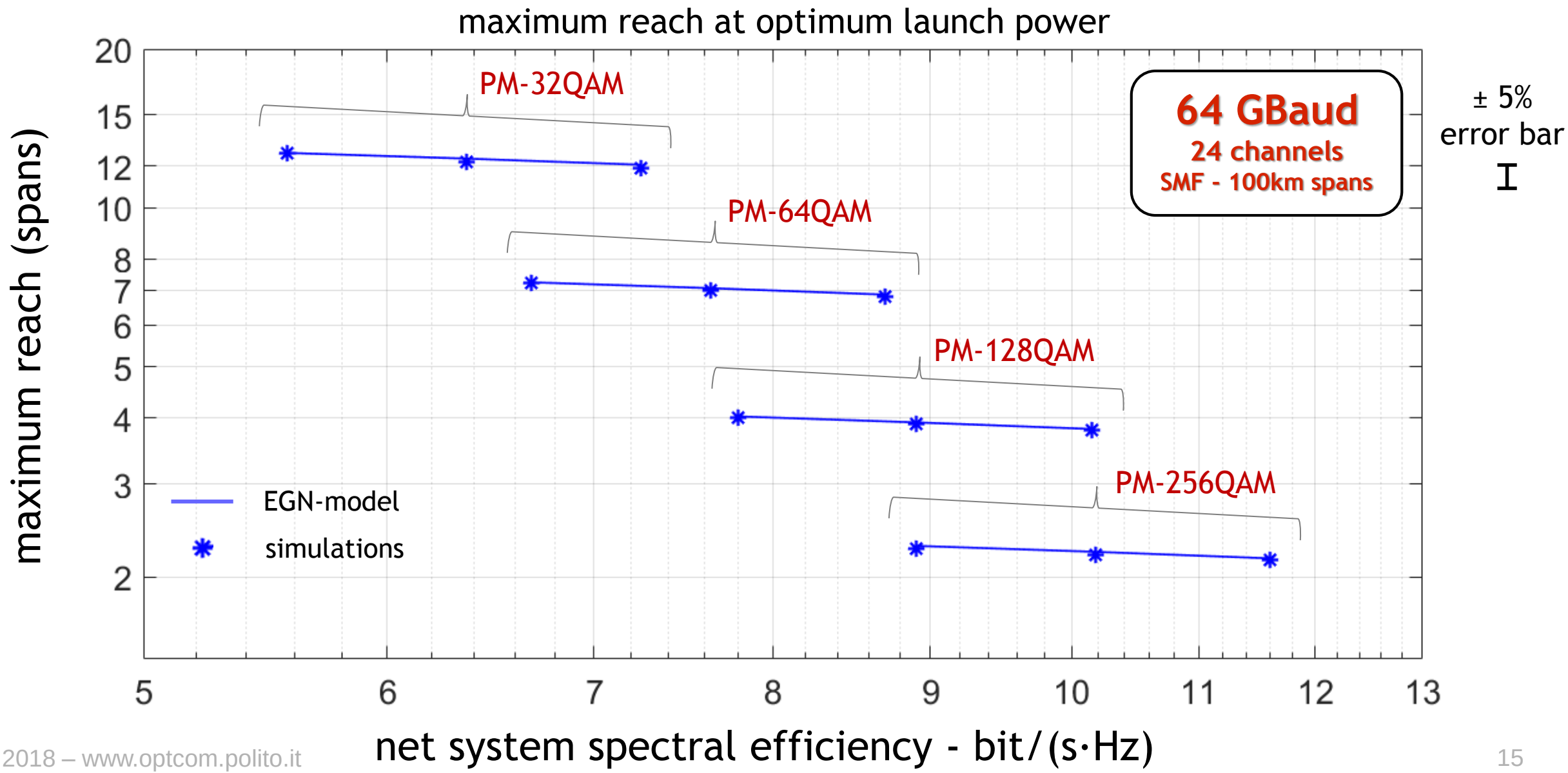
maximum reach at optimum launch power




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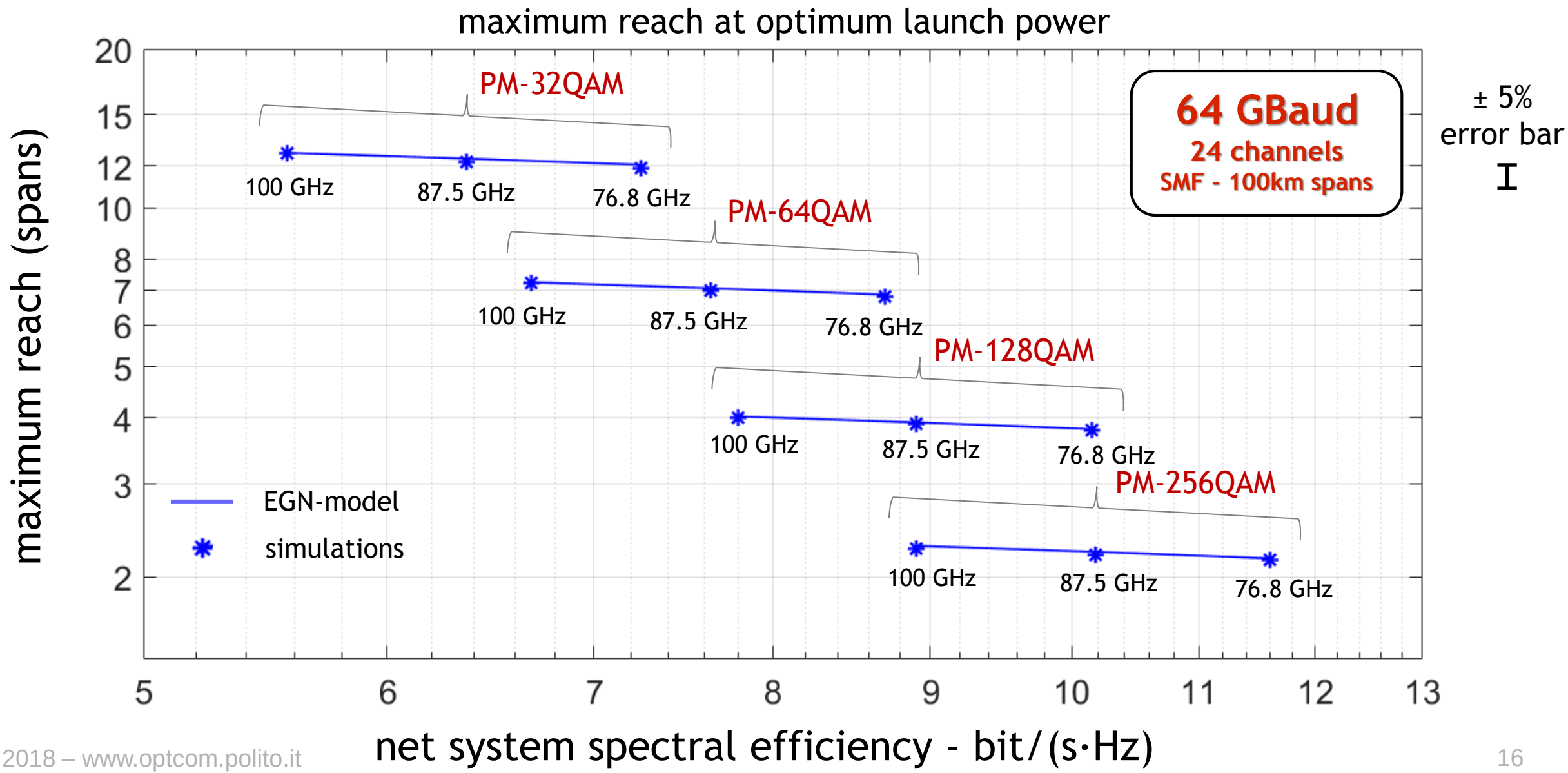
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
100 GHz
87.5 GHz
76.8 GHz
64 GBaud
24 channels
SMF - 100km spans
± 5%
error bar
EGN-model
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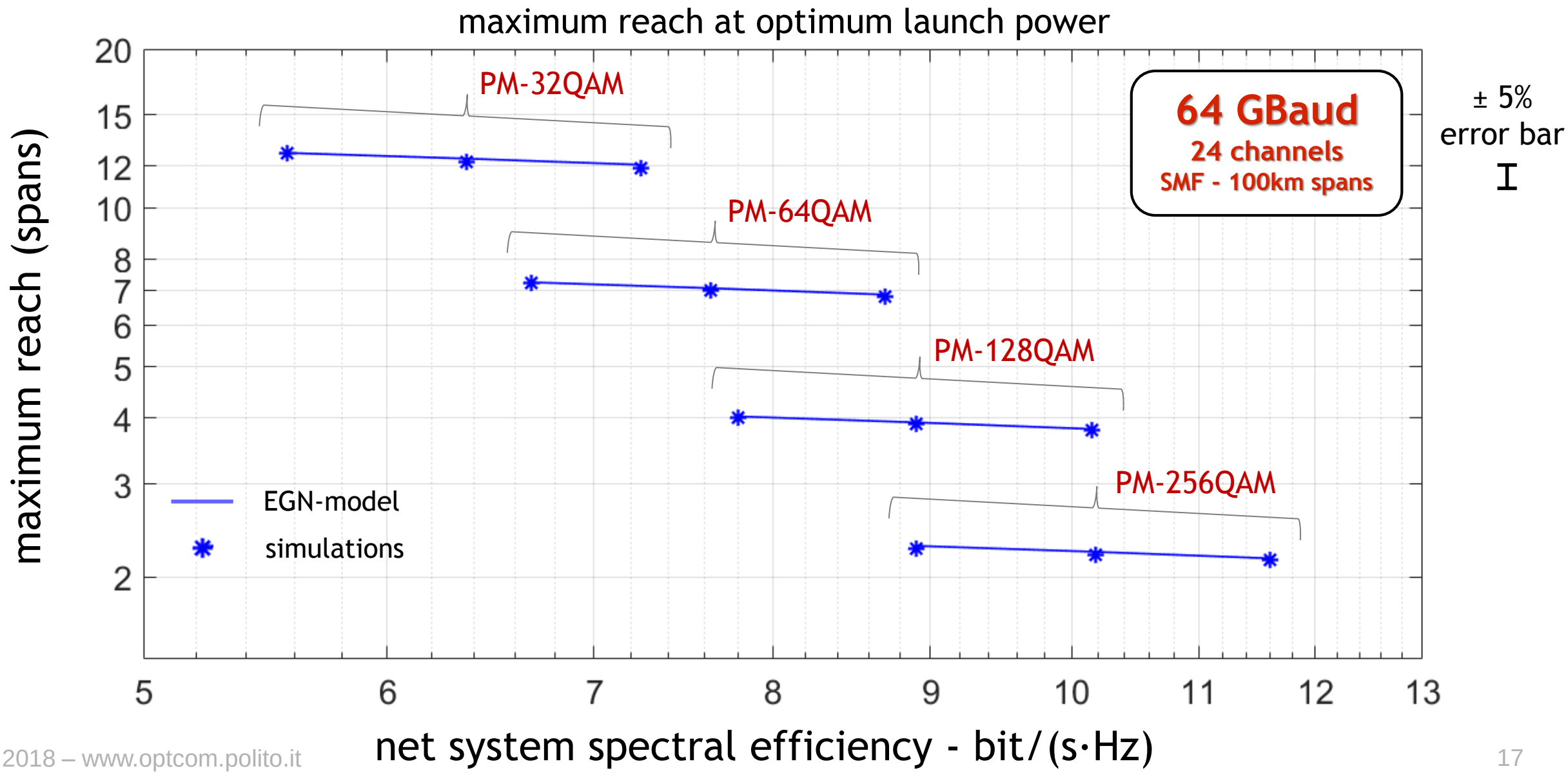
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
64 GBaud
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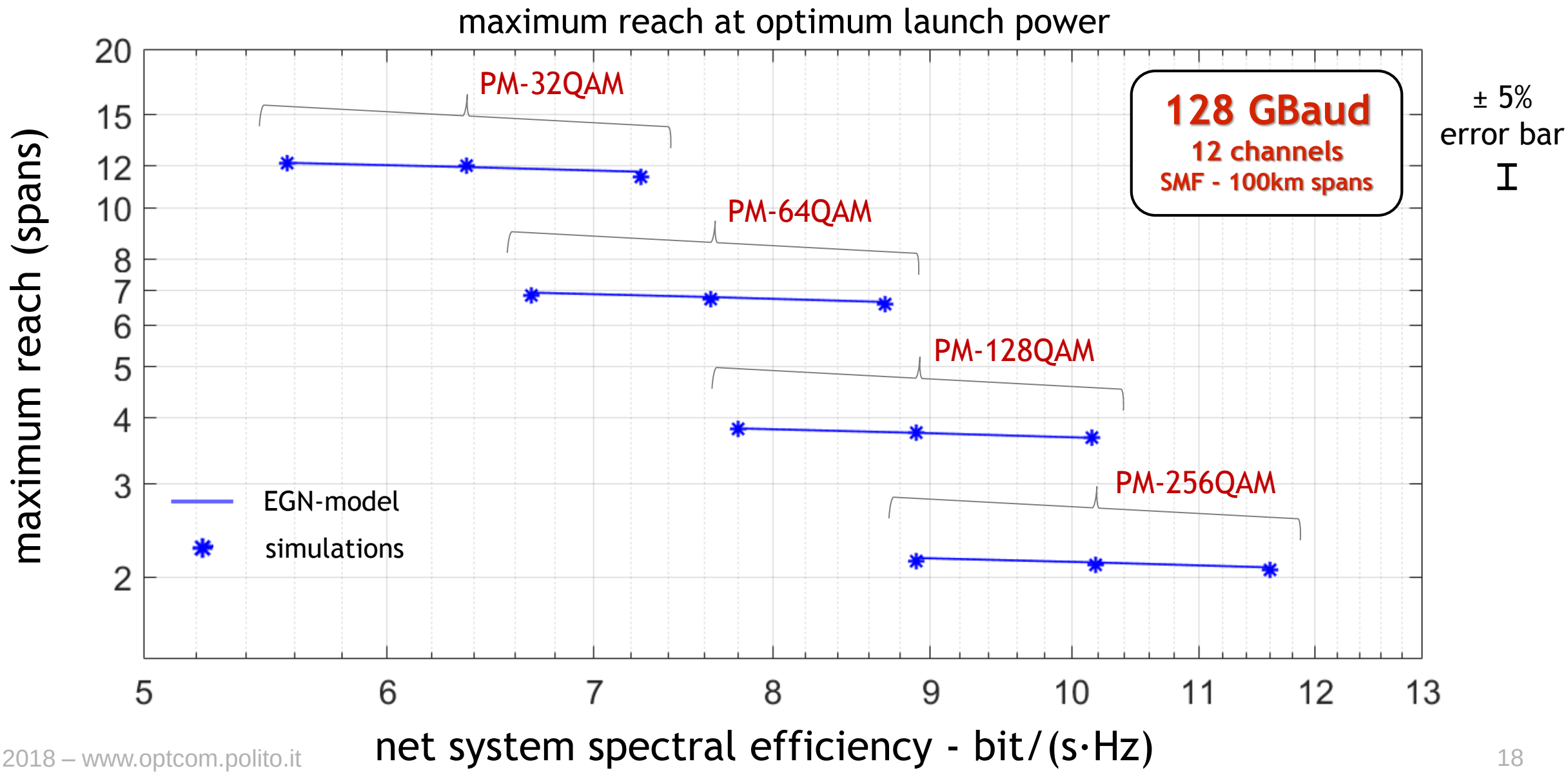
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
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SMF - 100km spans
± 5%
error bar
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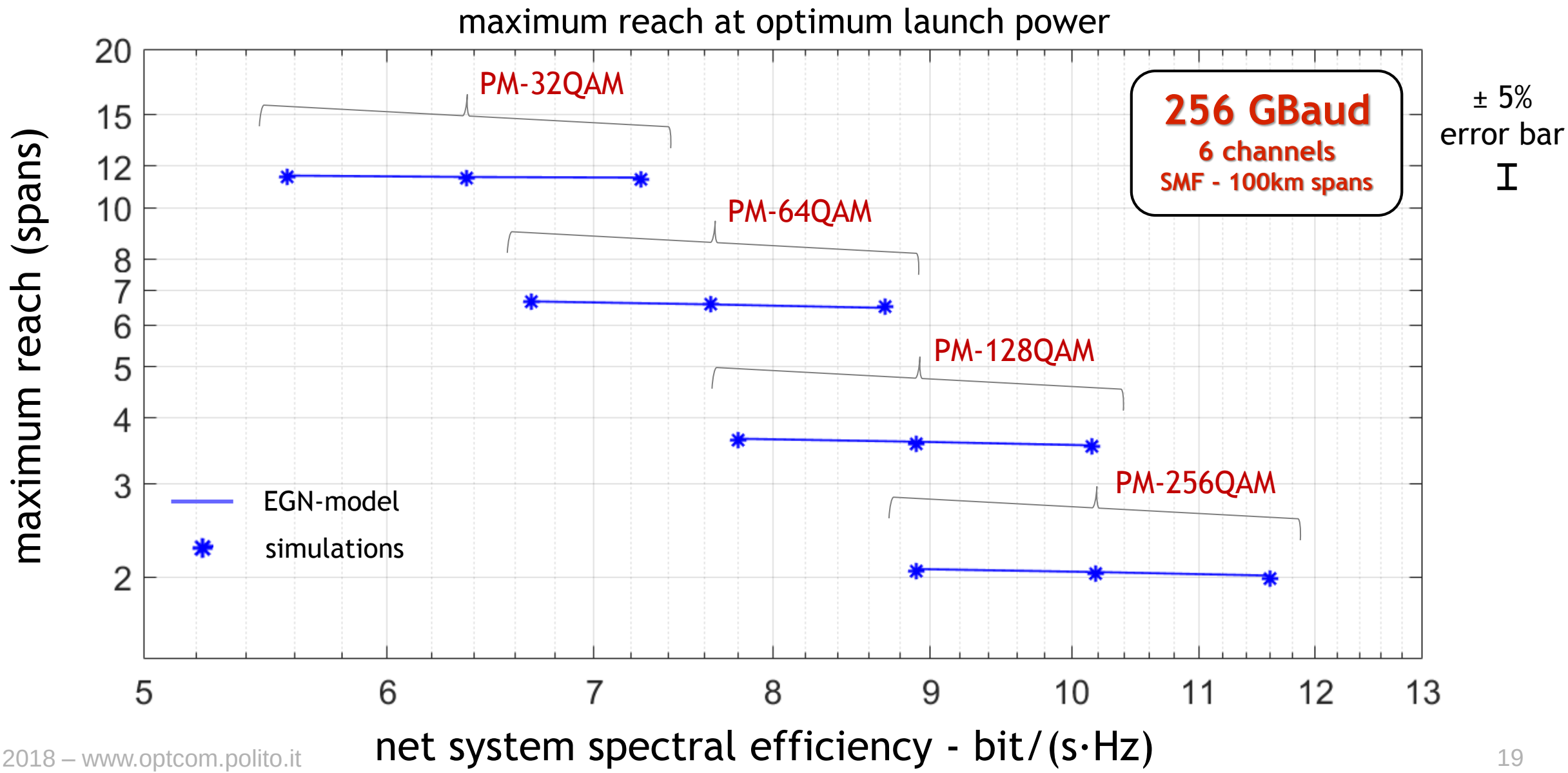
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
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SMF - 100km spans
EGN-model
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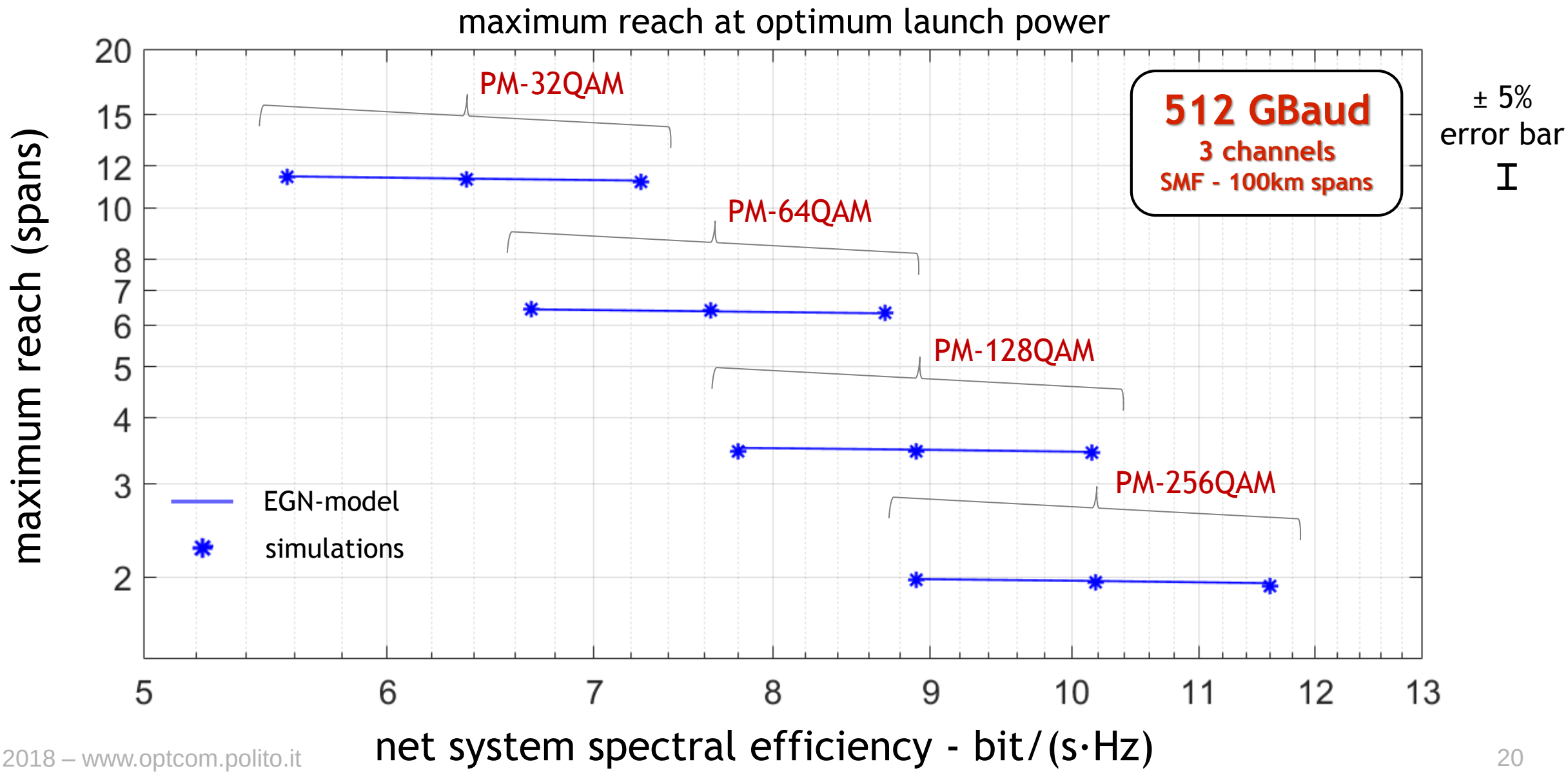
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
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PM-256QAM
512 GBaud
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SMF - 100km spans
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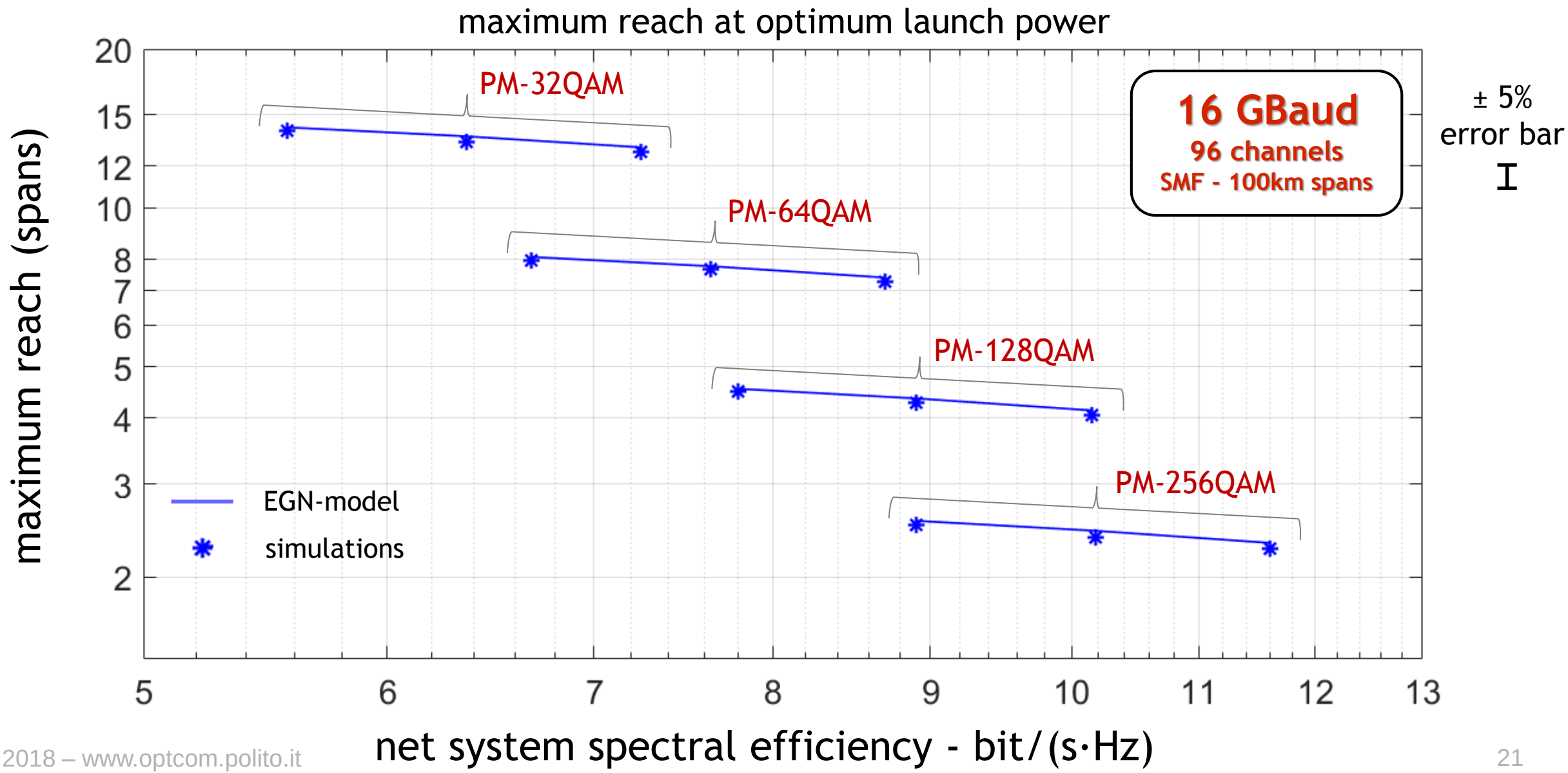
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
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PM-128QAM
PM-256QAM
16 GBaud
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SMF - 100km spans
EGN-model
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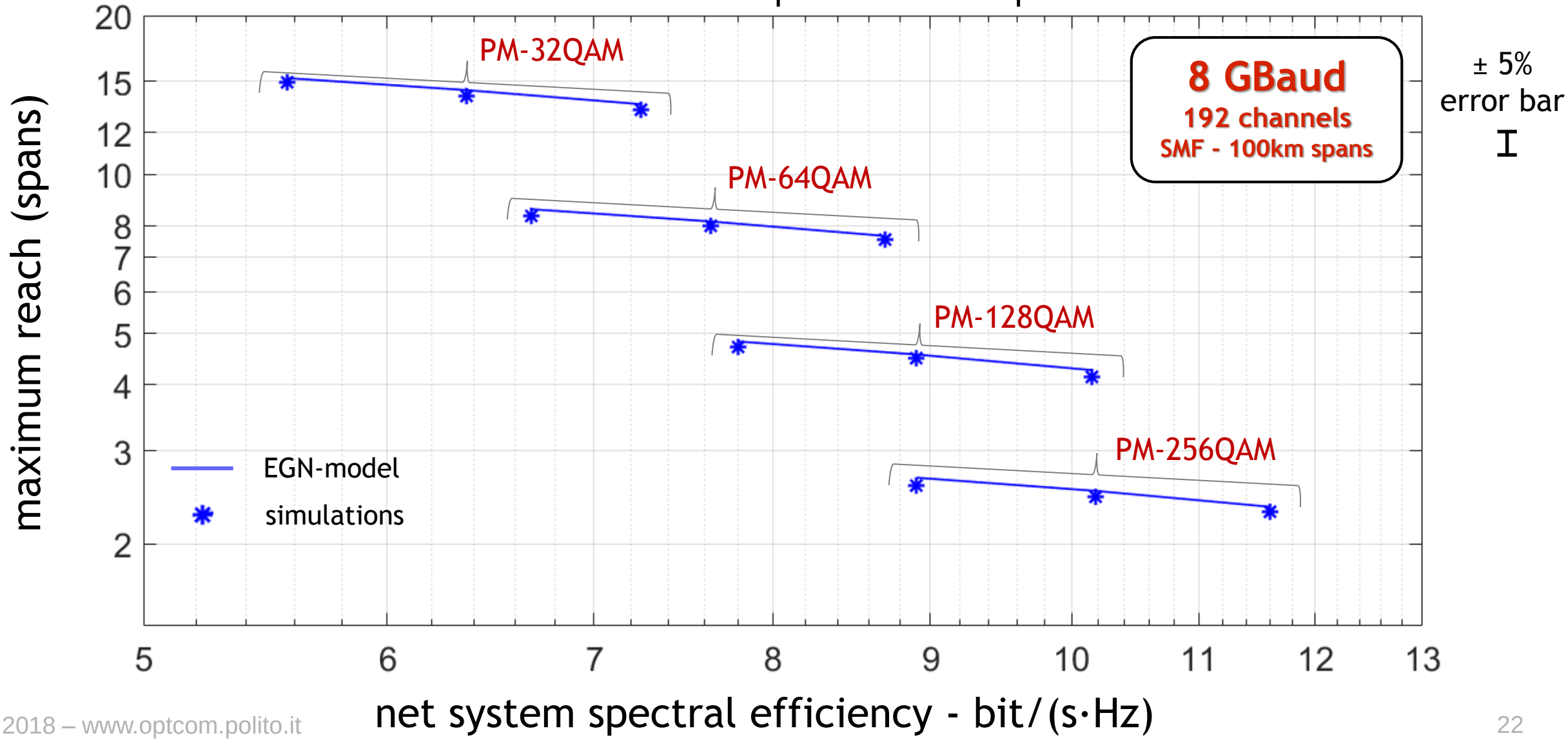
maximum reach at optimum launch power



± 5% error bar

Key take-away

- the EGN-model is **very accurate across any conceivable symbol rate**
- also at low dispersion (D=2) and with shorter spans (60 km)
- using either GMI or pre-FEC BER as performance parameter

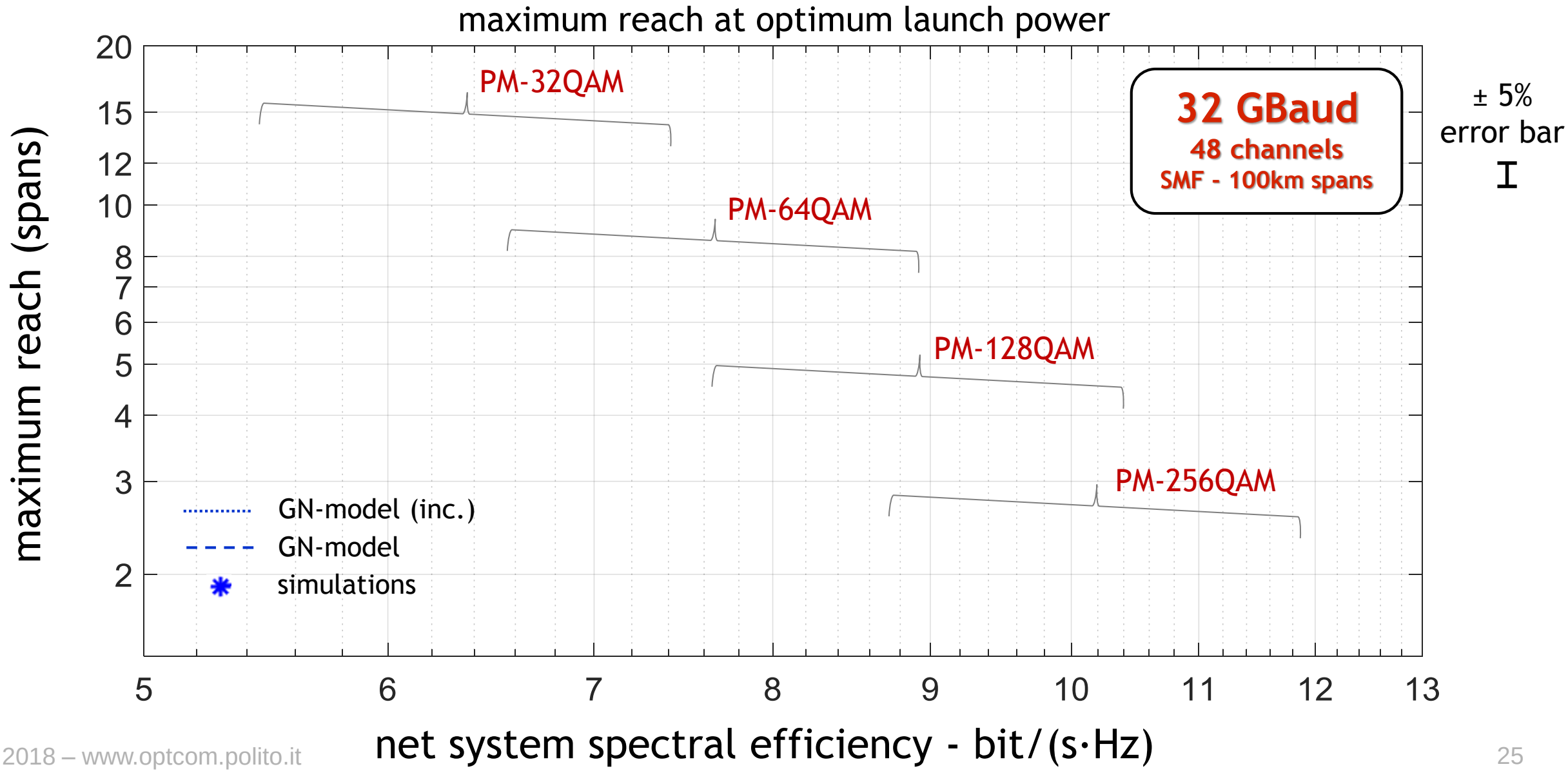
what about the GN model?

- The EGN-model has great performance 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
  - especially in its simplest form: *the incoherent GN-model* (or iGN-model)

- At 32 GBaud the GN-model is “pessimistic”
  - → it underestimates max reach by 5% (long systems) to 15% (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
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PM-256QAM
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SMF - 100km spans
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GN-model (inc.)
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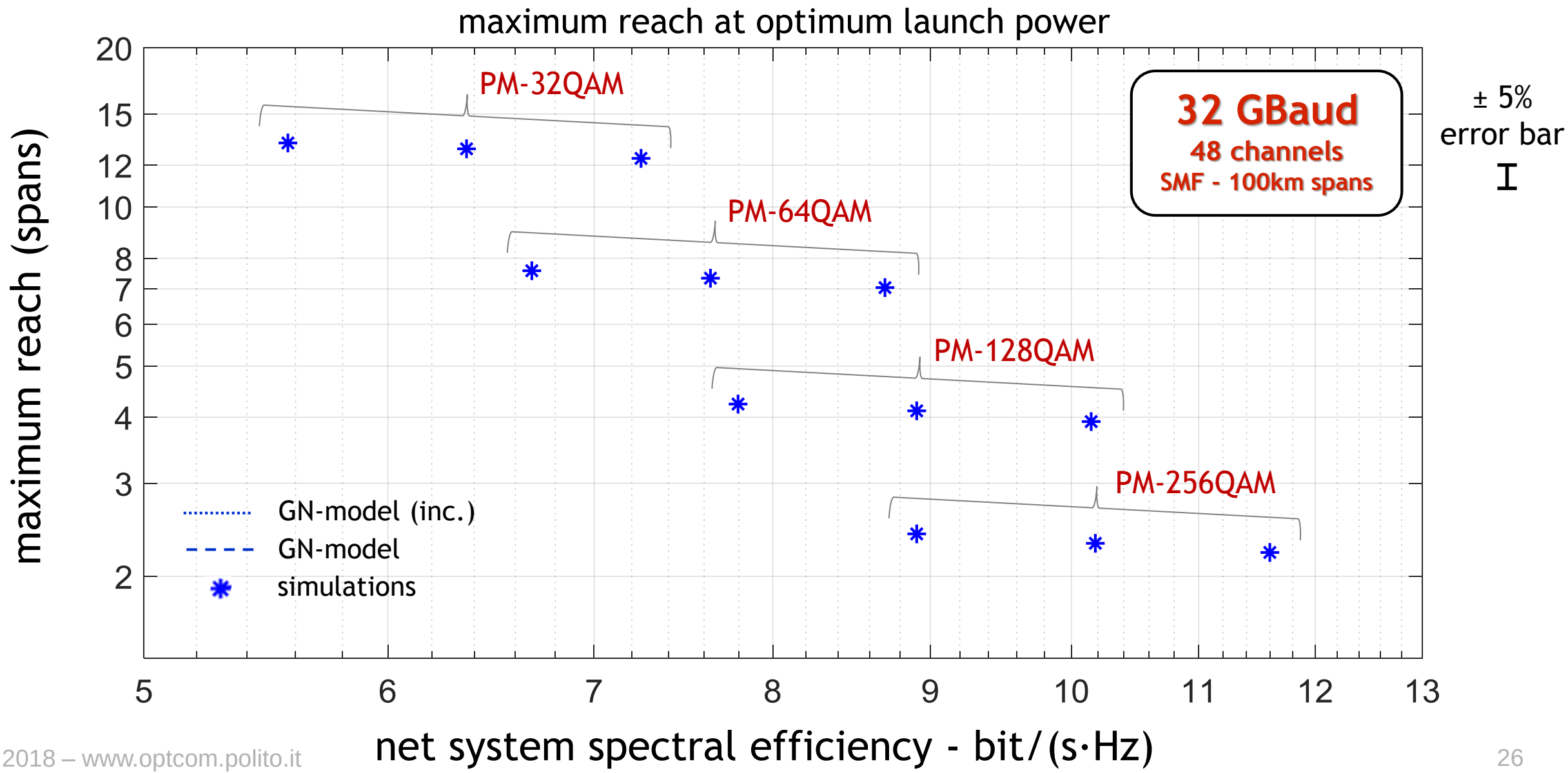
maximum reach at optimum launch power
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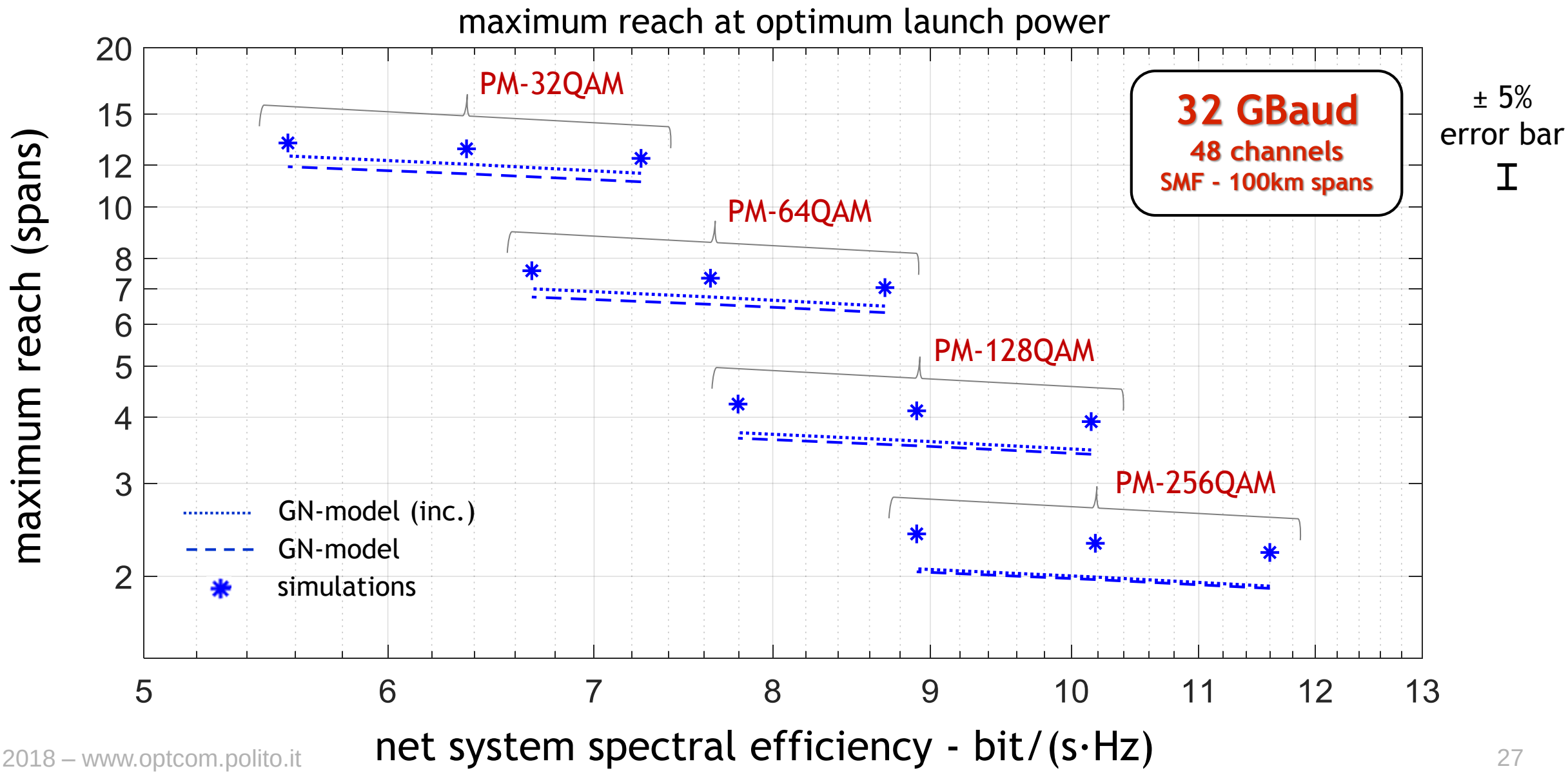
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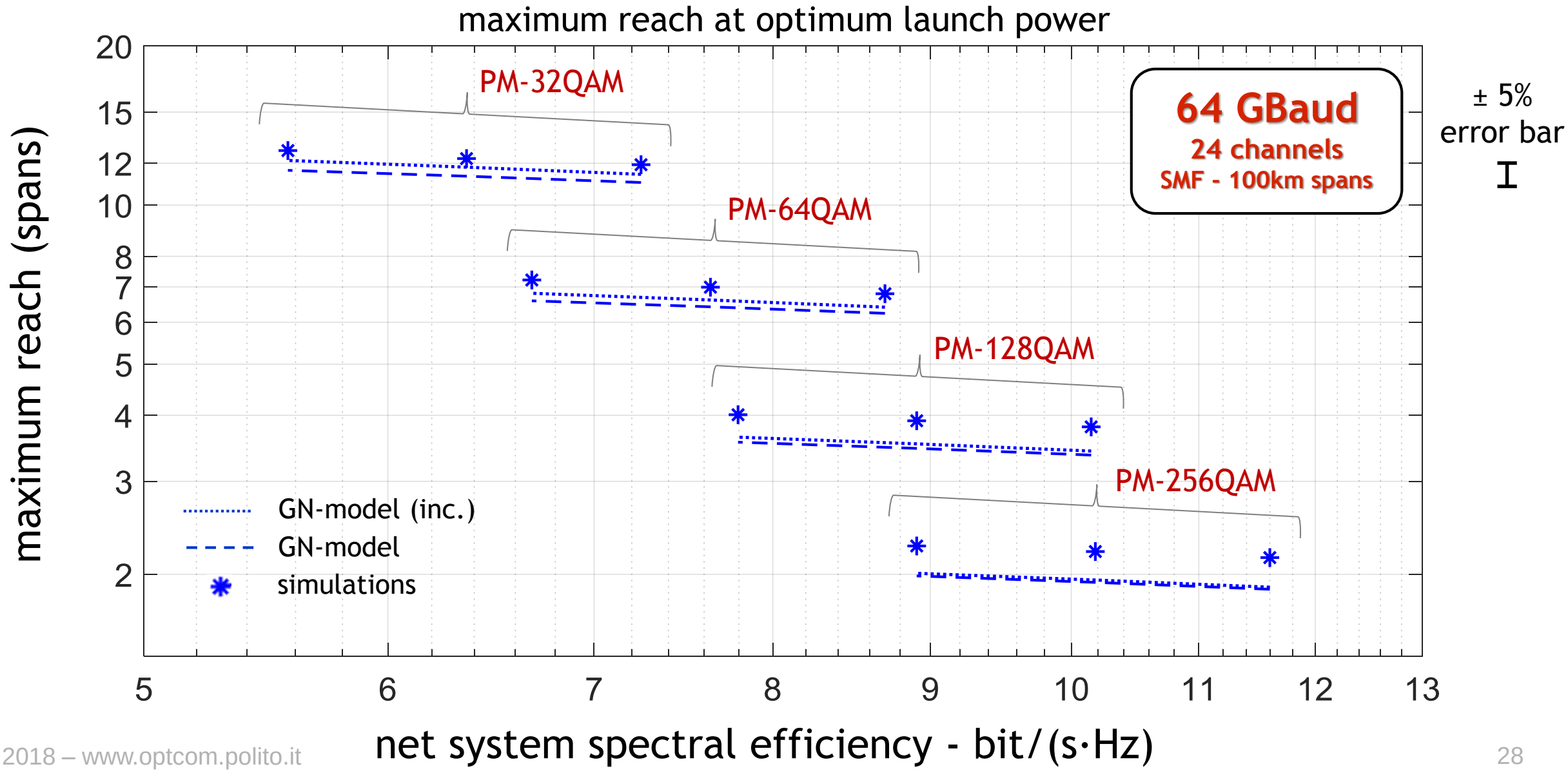
maximum reach at optimum launch power
maximum reach (spans)
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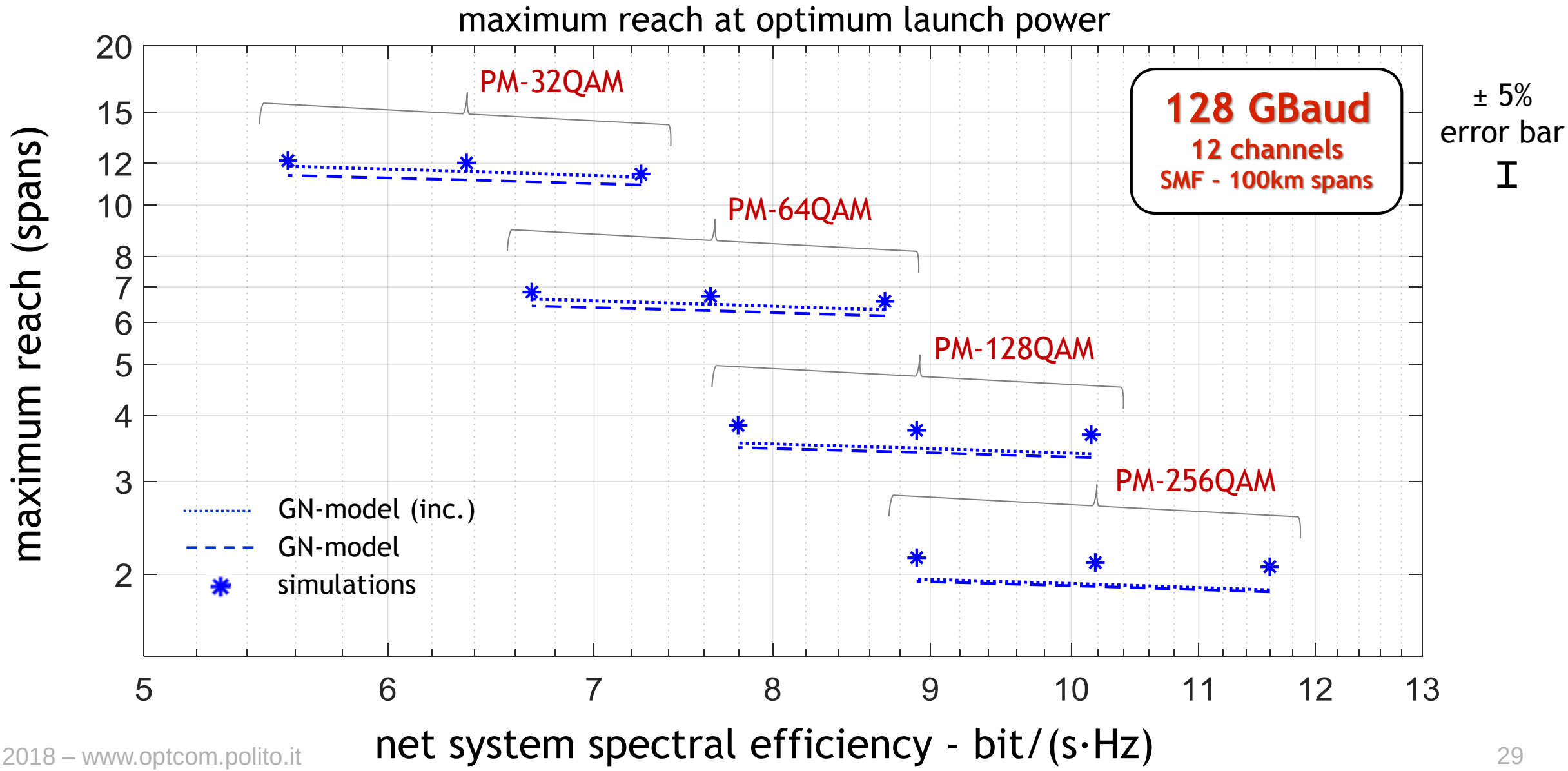
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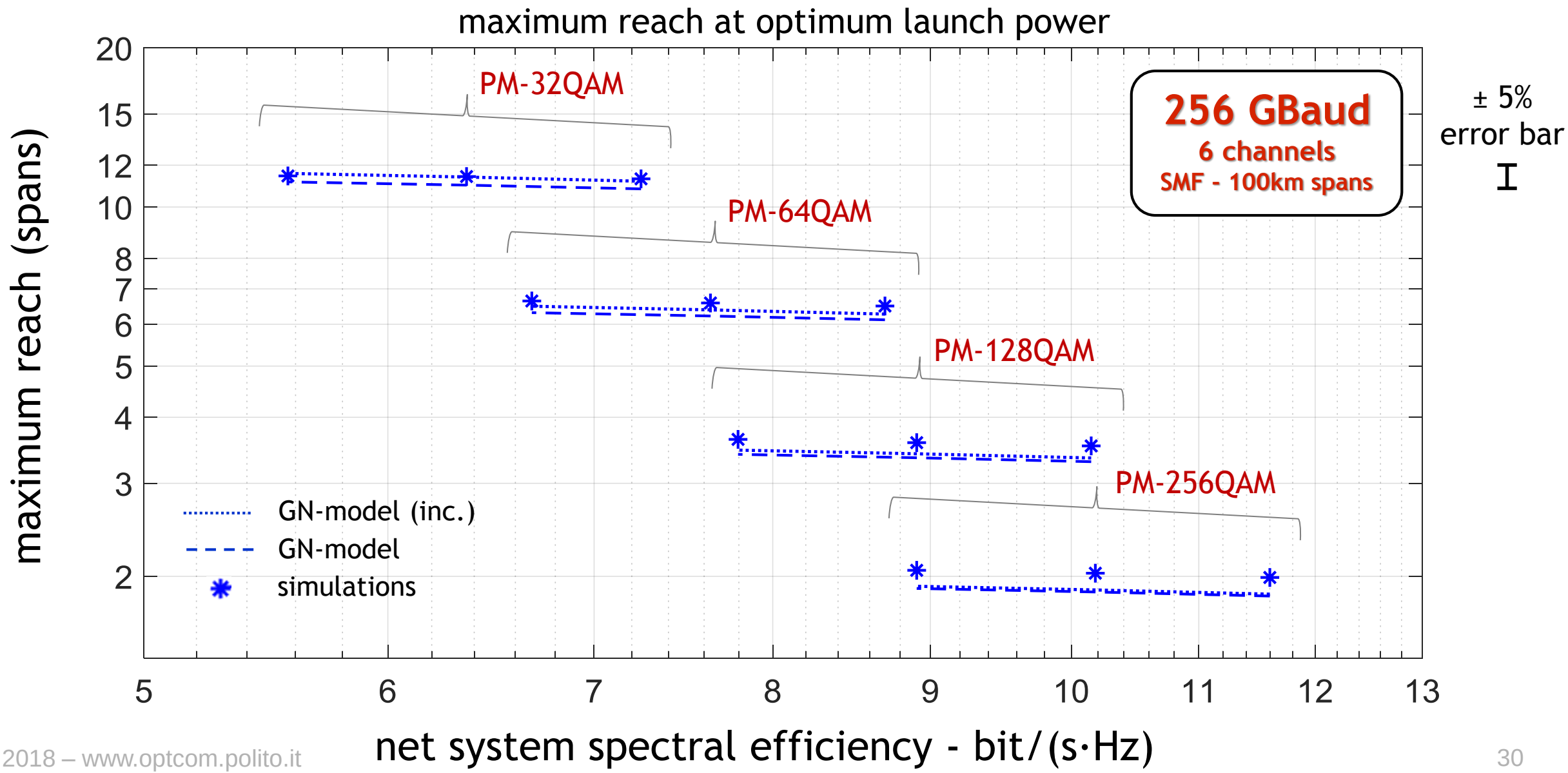
maximum reach at optimum launch power
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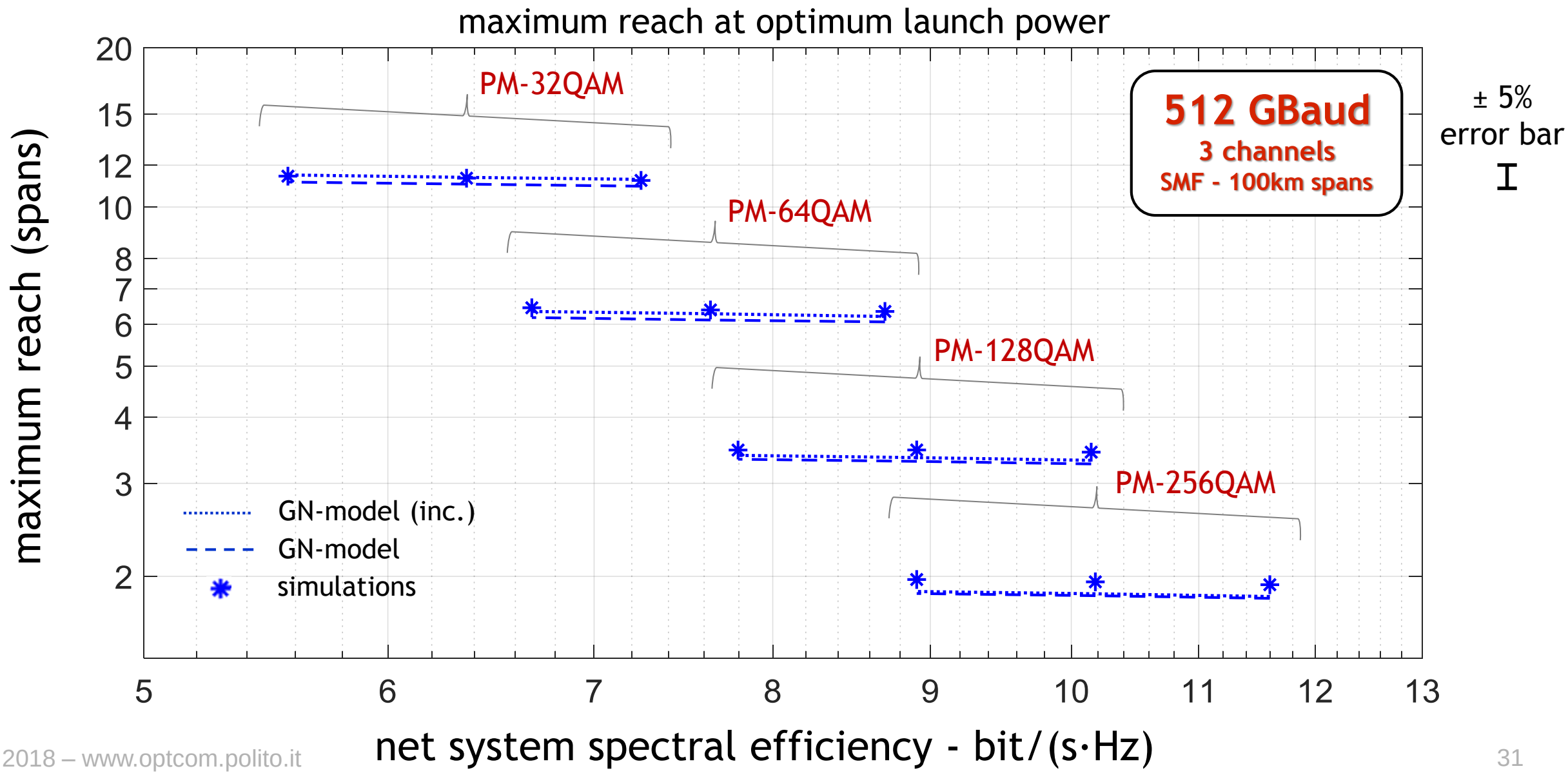
maximum reach at optimum launch power
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Key take-away

- 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/

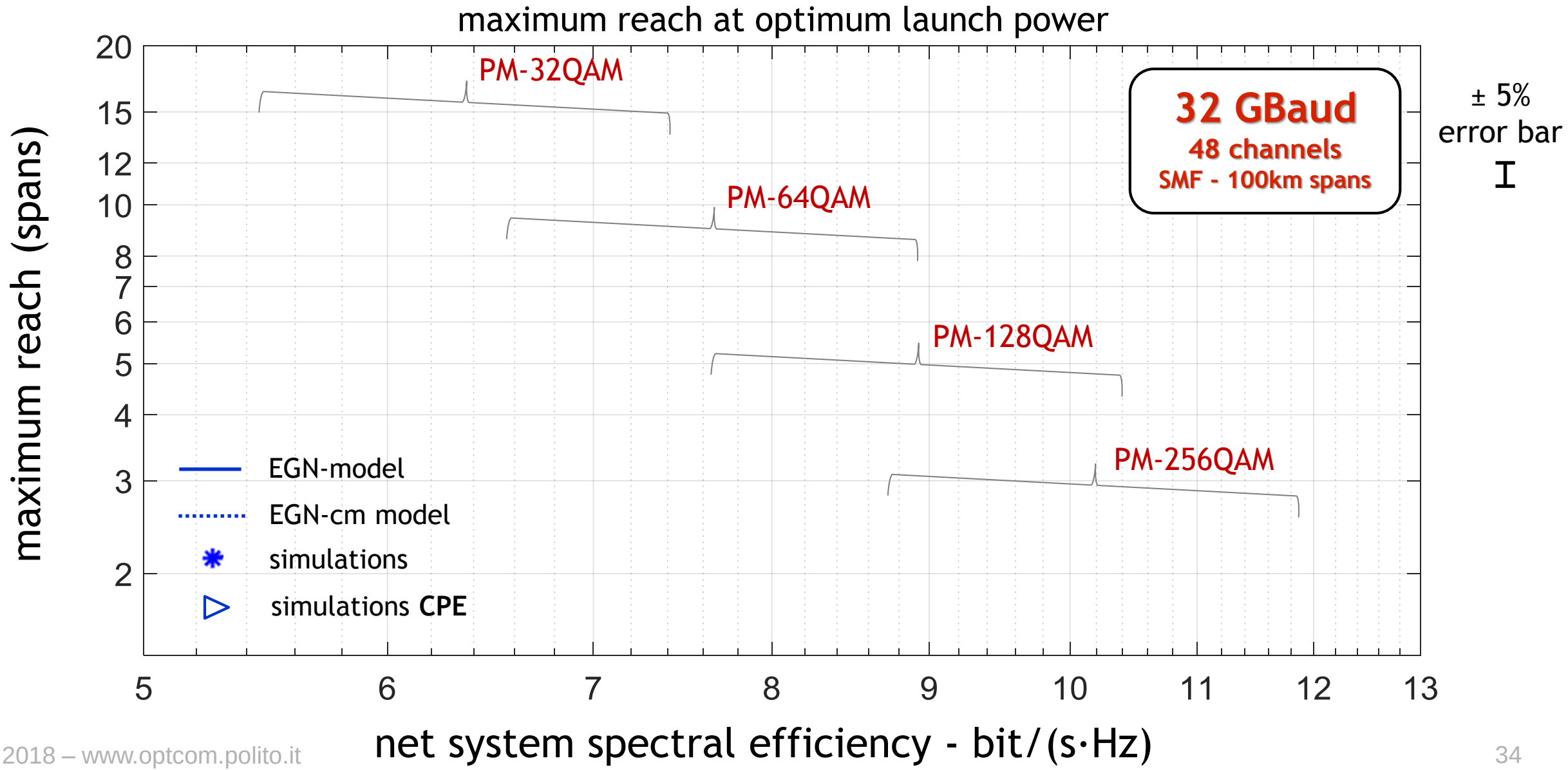
Non-linear phase noise (NLPN)

- The previous simulations performed no attempt at non-linear phase noise (NLPN) mitigation

- We are now going to use an ideal CPE, of the «**genie**» type, as done in:
  - T. Fehenberger, M. P. Yankov, L. Barletta, and N. Hanik, "Compensation of XPM interference by blind tracking of the nonlinear phase in WDM systems with QAM input," ECOC, Sep. 2015.
  - T. Fehenberger, N. Hanik, T. A. Eriksson, P. Johannisson, M. Karlsson, On the Impact of Carrier Phase Estimation on Phase Correlations in Coherent Fiber Transmission, Tyrrhenian Workshop 2015
  - M.P. Yankov et al., 'Nonlinear Phase Noise Compensation in Experimental WDM Systems with 256QAM' J. Lightw. Technol., vol. 35, no. 8, pp. 1438-1443, Apr. 2017.

- Essentially, it is a permanently data-driven CPE
- It provides an upper bound for the performance of averaging-based CPEs

- For comparison, we are going to look at the EGN model assuming *constant-modulus transmission*, because it provide an **approximate estimate of NLPN suppression**
- *What happens at ultra-high symbol rates?*


maximum reach at optimum launch power
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PM-32QAM
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SMF - 100km spans
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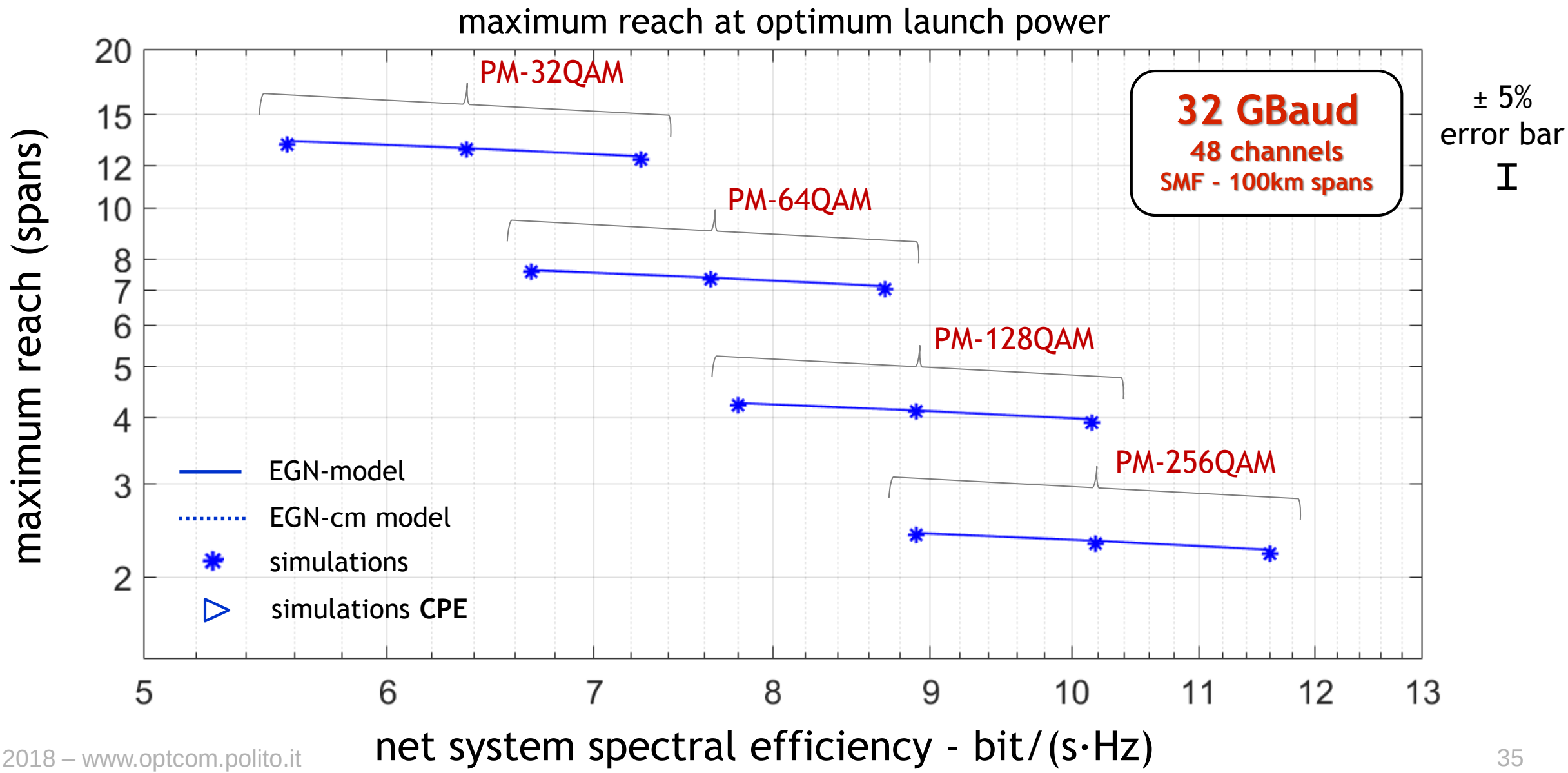
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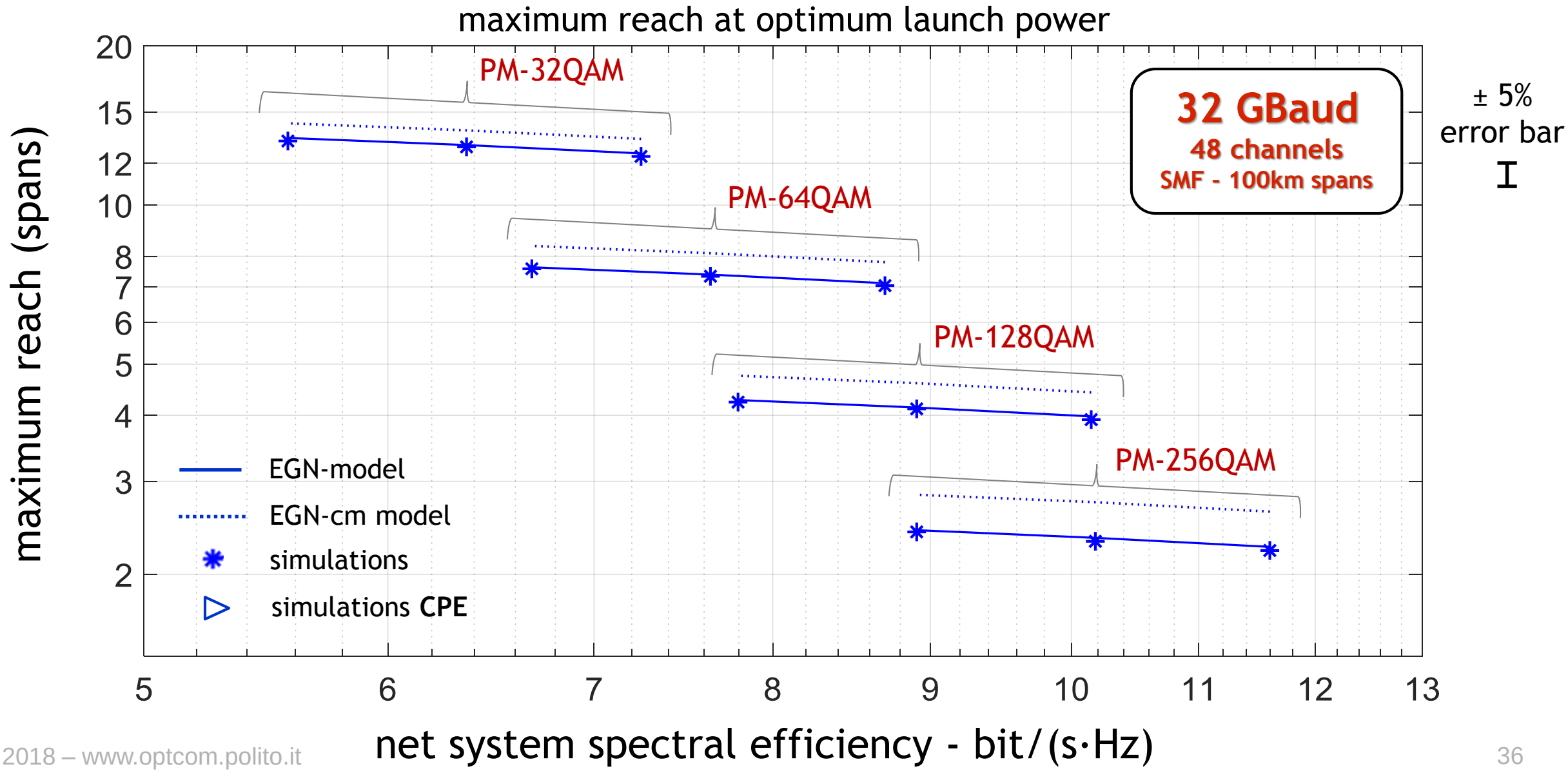
maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
32 GBaud
48 channels
SMF - 100km spans
± 5%
error bar
EGN-model
EGN-cm model
simulations
simulations CPE
20
15
12
10
8
7
6
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4
3
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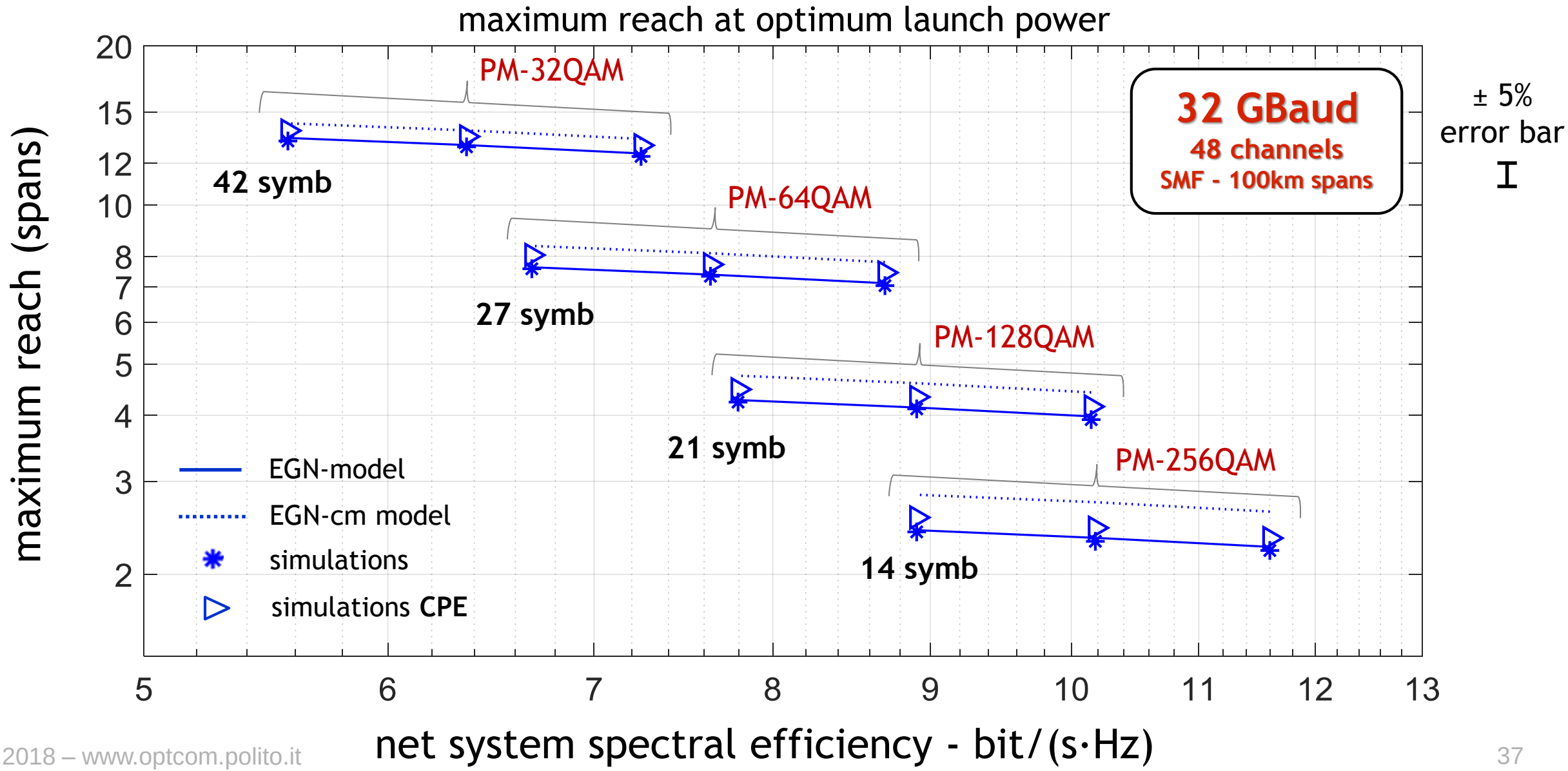
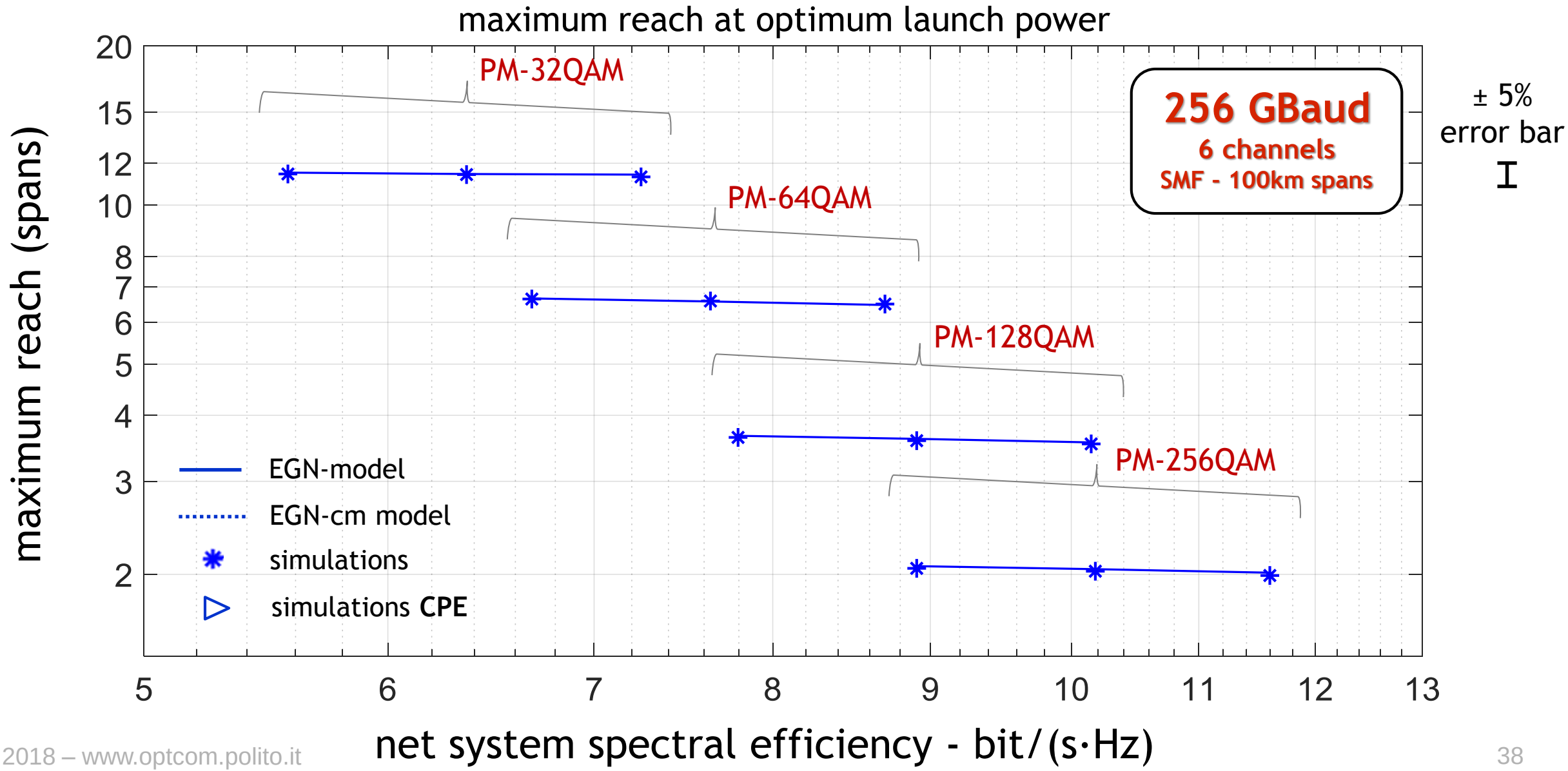
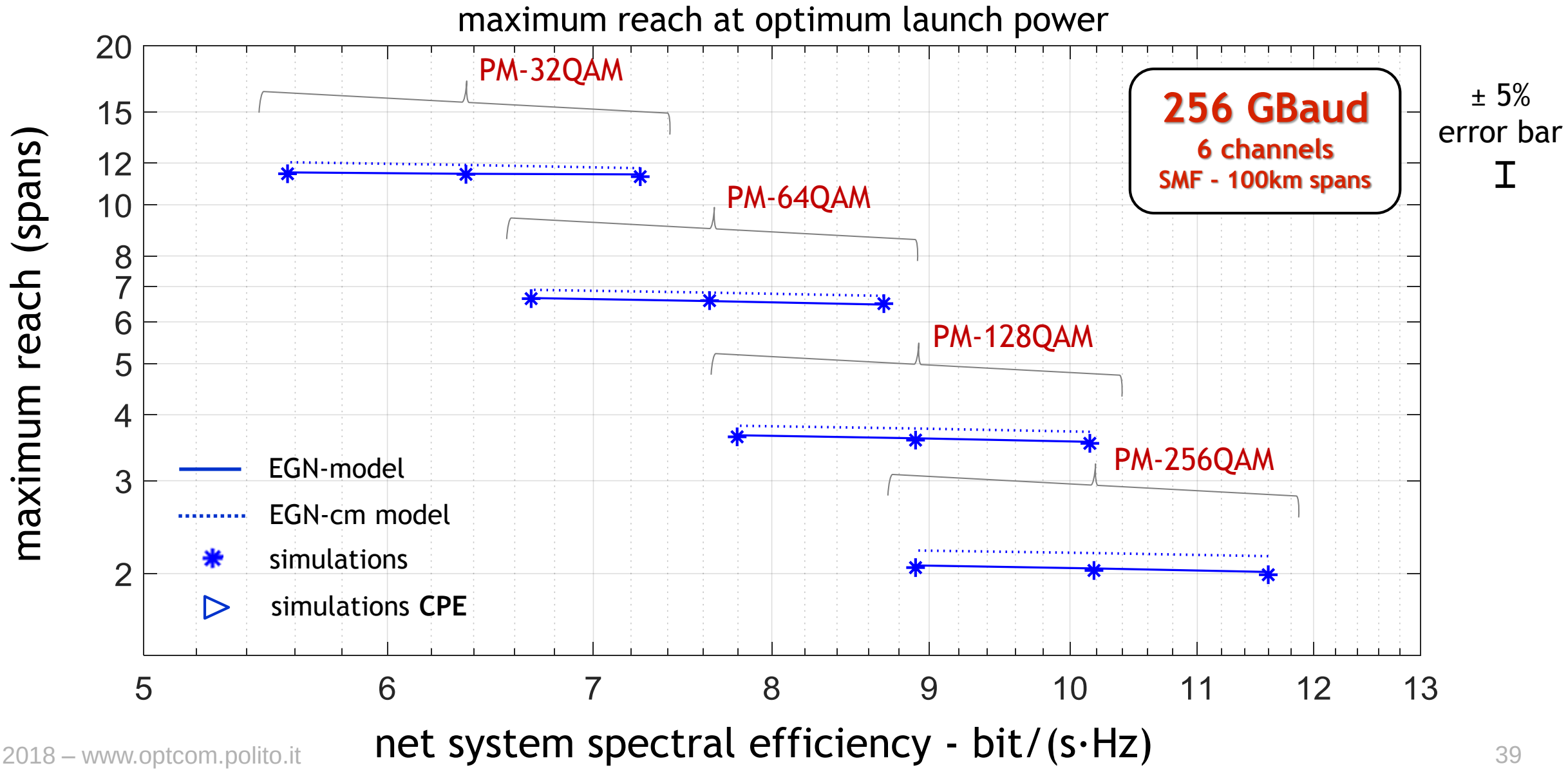
11
12
13


maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
42 symb
27 symb
21 symb
14 symb
32 GBaud
48 channels
SMF - 100km spans
± 5%
error bar
EGN-model
EGN-cm model
simulations
simulations CPE

the big picture




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
EGN-cm model
simulations
simulations CPE
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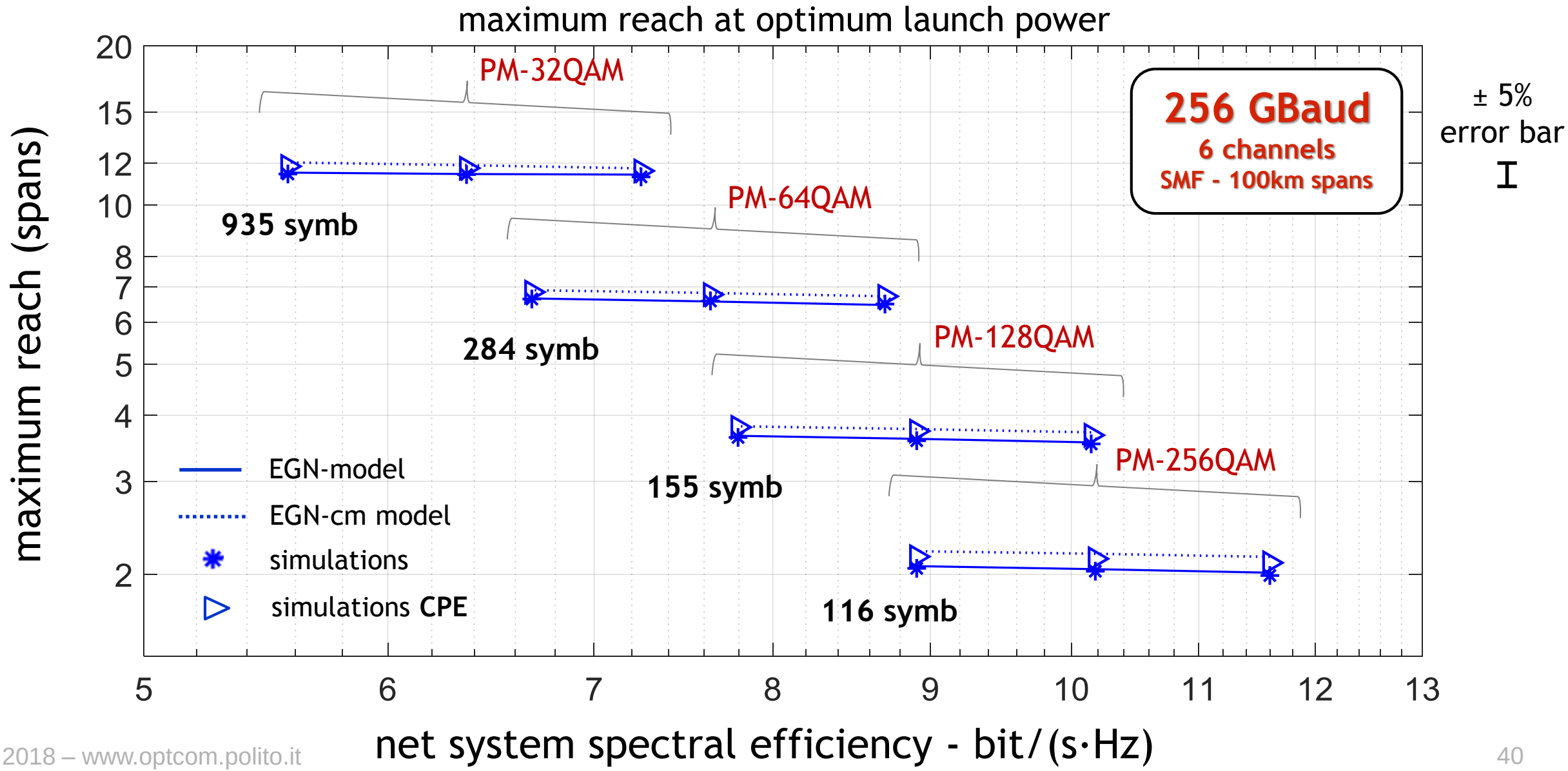
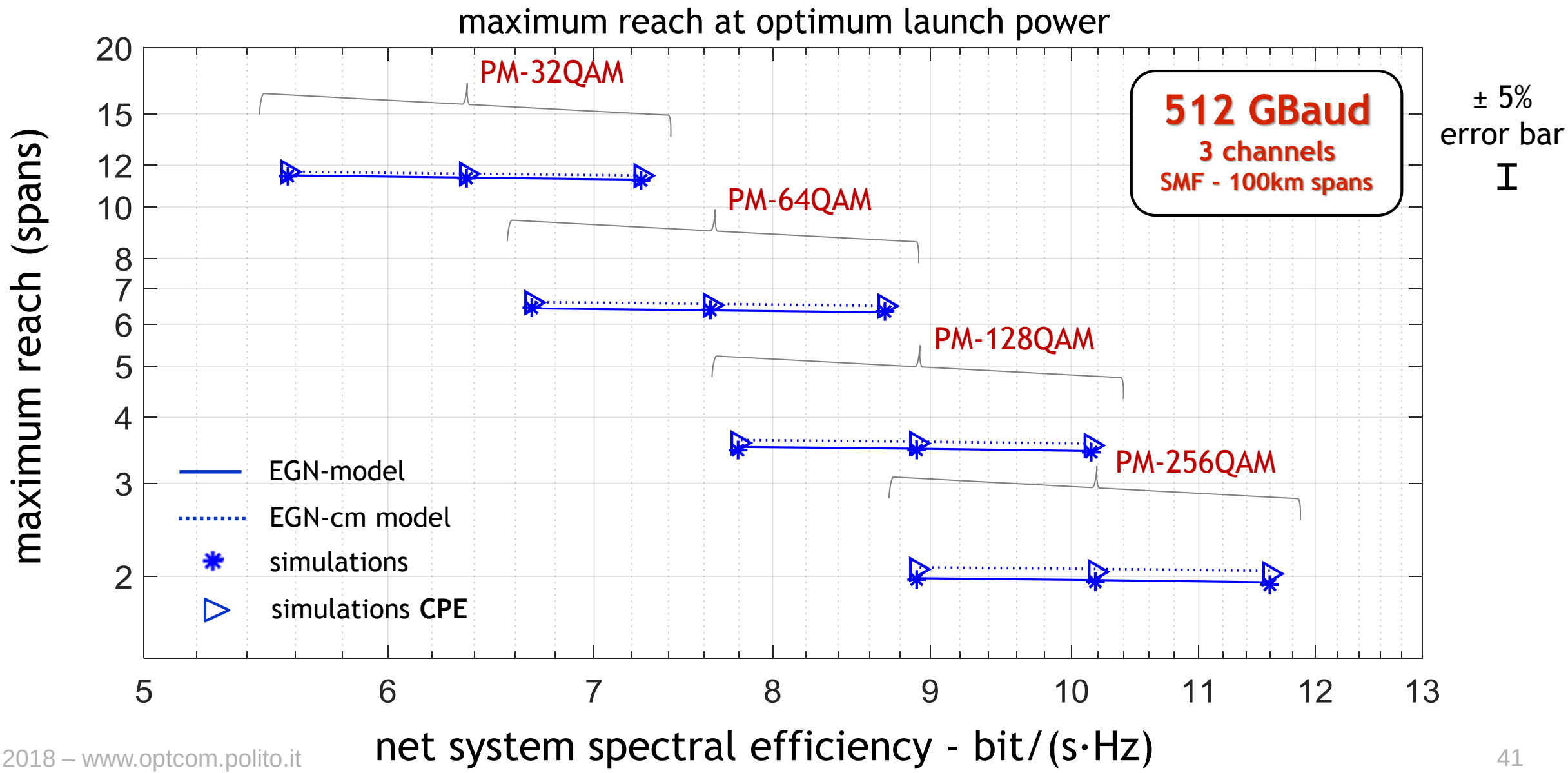

maximum reach at optimum launch power
maximum reach (spans)
net system spectral efficiency - bit/(s·Hz)
PM-32QAM
PM-64QAM
PM-128QAM
PM-256QAM
935 symb
284 symb
155 symb
116 symb
256 GBaud
6 channels
SMF - 100km spans
± 5%
error bar
EGN-model
EGN-cm model
simulations
simulations CPE


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
EGN-model
EGN-cm model
simulations
simulations CPE
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Key take-away

- Going towards high symbol rates:
  - NLPN decreases as shown by the EGN-cm model
  - Mitigating it is easier
- Overall, its impact decreases

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- Results appear in general agreement with the theory in the excellent paper:

R. Dar and P. J. Winzer “Nonlinear interference mitigation: methods and potential Gain,” J. Lightwave Technology, vol. 35, pp. 903-930 (2017)

- And also with the results on the following page.

long-correlated phase noise

- The first paper (in “coherent systems” time) that closed-form characterized the long-correlation of LC-PN:

Marco Secondini and Enrico Forestieri, “Analytical Fiber-Optic Channel Model in the Presence of Cross-Phase Modulation”, PTL, vol. 24, pp. 2016-2019, Nov. 2012

- Several other papers have addressed phase noise since:
  - M. Secondini, E. Forestieri, and G. Prati, “Achievable information rate in nonlinear WDM fiber-optic systems with arbitrary modulation formats and dispersion maps,” J. Lightwave Technol. 31, 3839–3852 (2013).
  - R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, ‘Properties of nonlinear noise in long, dispersion-uncompensated fiber links,’ *Optics Express*, vol. 21, no. 22, pp. 25685-25699, Nov. 2013.
  - R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, ‘Accumulation of nonlinear interference noise in fiber-optic systems,’ *Optics Express*, vol. 22, no. 12, pp. 14199-14211, June 2014.
  - M. Secondini, E. Forestieri, “On XPM Mitigation in WDM Fiber-Optic Systems”, PTL, vol. 26, pp. 2252- 2255, Nov. 2014.
  - R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, ‘Inter-Channel Nonlinear Interference Noise in WDM Systems: Modeling and Mitigation,’ *J. of Lightwave Technol.*, vol. 33, no. 5, pp. 1044-1053, Mar. 2015.
  - R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, ‘Pulse collision picture of inter-channel nonlinear interference in fiber-optic communications,’ *J. of Lightwave Technol.*, vol. 34, no. 2, pp. 593-607, Jan. 2016.
- Some very interesting experimental work has been done as well :
  - T. Fehenberger, N. Hanik, T. A. Eriksson, P. Johannisson, M. Karlsson, “On the Impact of Carrier Phase Estimation on Phase Correlations in Coherent Fiber Transmission”, 2015 Tyrrhenian International Workshop on Digital Communications (TIWDC), available on IEEE Xplore.
  - Carsten Schmidt-Langhorst, Robert Elschner, Felix Frey, Robert Emmerich, Colja Schubert, “Experimental Analysis of Nonlinear Interference Noise in Heterogeneous Flex-Grid WDM Transmission”, ECOC 2015, paper Tu.1.4.3, Sept. 2015.

Key take-away

- For Gaussian constellations,
  - the GN-model coincides with the EGN-model
  - so we have the EGN model accuracy at all rates, with the complexty of the GN

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
  - The GN-model is as accurate as EGN for Gaussian constellations
  - NLPN appears to decrease as shown by the EGN-cm model as rates go up

- In general, the good news is that NLI modeling appears to become ***easier*** at larger symbol rates

thank you !

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