Link Performance Analysis of Multi-User Detection Techniques for W-band Multi-Beam Satellites

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Outline

- **Introduction and motivation;**
- **Multi-beam satellite system description;**
- **Multi-user detection (MUD) strategies for multi-beam satellites;**
- **Simulation strategy and results;**
- **From MUD performance assessment to MUD practical implementation;**
- **Conclusion and future work**

Introduction and motivation (1)

- **The use of multiple spot beams in modern broadband satellites has increased during the last few years;**
- **In some recent works[1], it has been shown that multi-beam satellites might boost the available data rate very close to 1 Tb/s in Ka-band (e.g. 750 Gb/s);**
- **The exploitation wider frequency spaces in EHF bands (Q-V band and W-band) in conjunction with multi-beam satellites should allow to fill the gap to the "terabit connectivity"[2];**
- **The issues to be solved are related to the management of the inter-beam interference, very relevant when aggressive frequency reuse is performed.**

Introduction and motivation (2)

- **Some works have been presented in recent literature dealing with the improvement of (Shannon's) capacity provided by multi-beam interference rejection[3];**

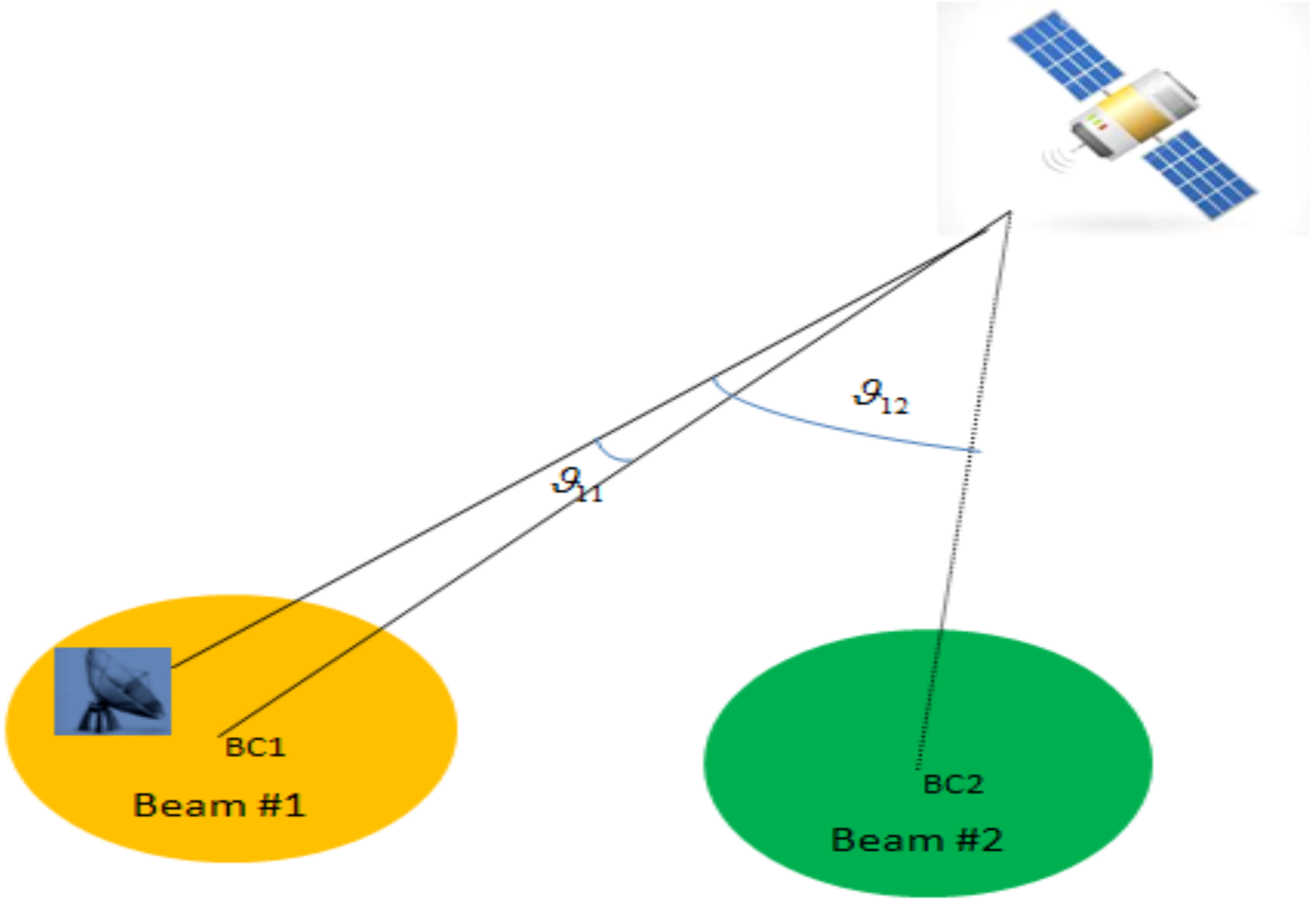
- **Other works considers the impact of multi-beam interference on link satellite budget[4];**

- **At our best knowledge, very few works deal with the analysis of the interference mitigation techniques;**

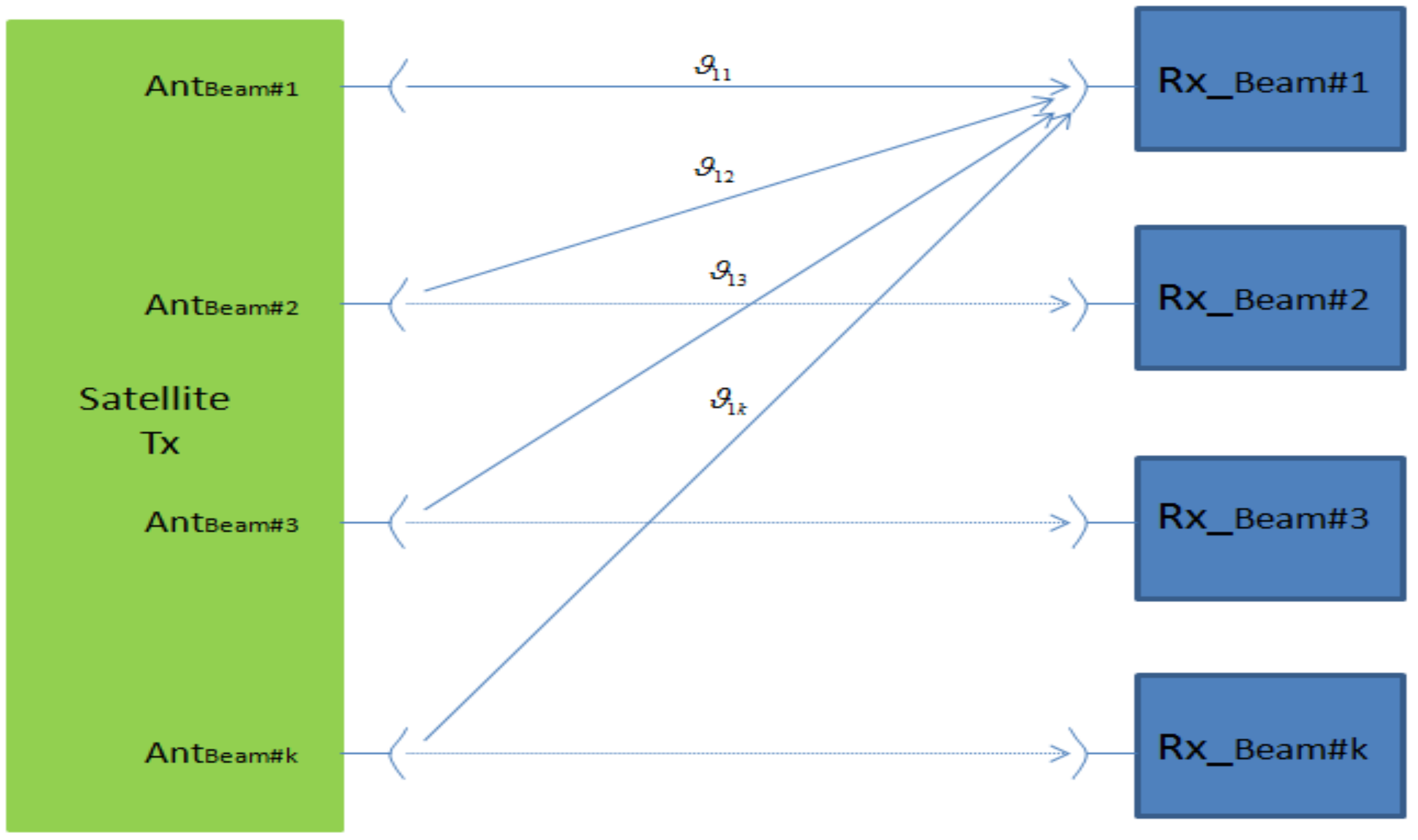
- **In our paper, we analyze, in terms of link performance, theoretical multi-user detection techniques (optimum *Maximum Likelihood* detection and sub-optimum linear *Minimum Mean Square Error* detection) in the innovative framework of a *W*-band multi-beam satellite system with aggressive frequency reuse.**

Multi-beam satellite system description (1)

- **General description**
  - **A system of *K* beams with full frequency reuse at a downlink frequency of 76 GHz is assumed.**



Multibeam satellite geometric scenario



Multibeam satellite transmission scenario

Multi-beam satellite system description (2)

- **Received multi-beam signal**

  - **Below, it is given the equations related to the multi-beam signal received by the generic *i*th beam receiver during the generic *n*th signaling interval:**

$$y_i(nT) \hat{=} y_{i,n} = g_{ii} S_{i,n} + \sum_{\substack{j=1 \\ j \neq i}}^{K} g_{ij} S_{j,n} + w_n$$

Received signal sample

$$\overline{G} = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1K} \\ g_{21} & g_{22} & \cdots & g_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ g_{K1} & g_{K2} & \cdots & g_{KK} \end{bmatrix}$$

Multi-beam channel matrix

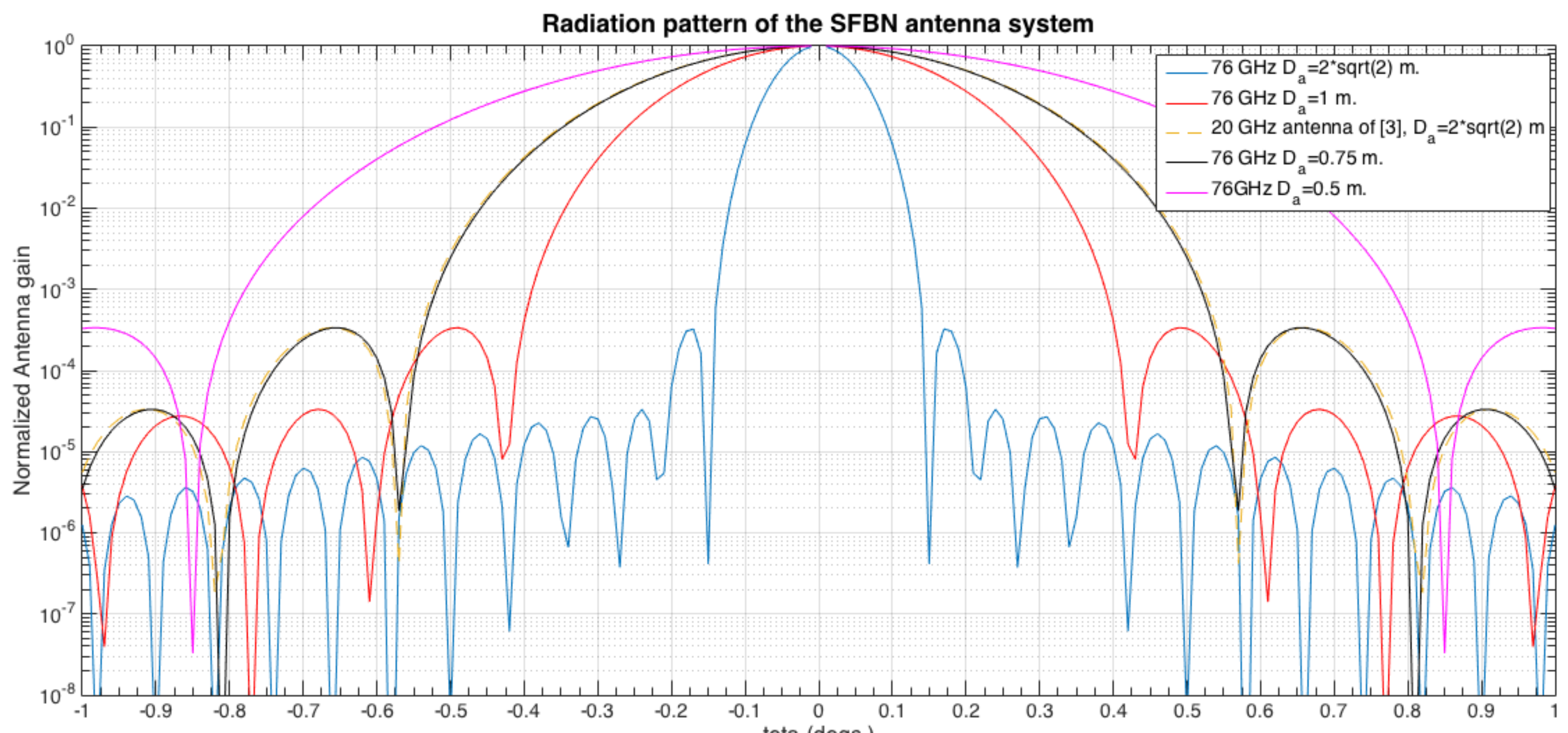
$$g_{ij} = \sqrt{G\left(\theta_{ij}\right)}$$

→ **square root of the antenna gain between the satellite transmitter antenna for beam *j* and beam *i*, being θ_{ij} the angle that forms the receiver in the beam *i* towards the spot beam center *j***

Multi-beam satellite system description (3)

- **Satellite antenna model**
  - **We consider, according to[4], a Single-Feed per Beam Network (SFBN) antenna system. Antenna gain is given as follows[5]:**

$$G(u)=\frac{(p+1)(1-T)}{(p+1)(1-T)+T}\cdot\left(2\frac{J_1(u)}{u}+2^{p+1}p!\frac{T}{1-T}\frac{J_{p+1}}{u^{p+1}}\right) \qquad u=\pi\frac{D_a}{\lambda}\sin\theta$$



Radiation pattern of SFBN antenna for T=0.9 and p=2

ANTENNA PHOTO (COSIMO)

Multi-user detection for multi-beam satellites (1)

- **Optimum Maximum Likelihood (ML) multi-user detection**
  - **<u>Theoretical</u> ML detection is based on the following criterion[6]:**

$$\min_{S_{i,n}} \left\{ \left| y_{i,n} - \sum_{j=1}^{K} g_{ij} S_{j,n} \right|^2 \right\} \quad i = 1,\ldots,K$$

  - **In order to compute the optimum symbol vector for all *K* users, we should compute the aforesaid metric for the following numbers of M-ary symbols:**

$$N_s = 2^{\log_2(M)K}$$

Multi-user detection for multi-beam satellites (2)

- **Linear Minimum Mean Square Error (MMSE) detection**

  - **<u>Theoretical</u> MMSE detection is based on the minimization of the mean square error between the transmitted symbols and the soft decision variable[6]:**

$$\min_R \left\{ E\left[\left\| R\underline{y}_n - \underline{S}_n \right\|^2 \right] \right\} \qquad \underline{y}_n = G\underline{S}_n + \underline{w}_n$$

  - **The theoretical optimization yields to the following solution (called *Wiener solution*):**

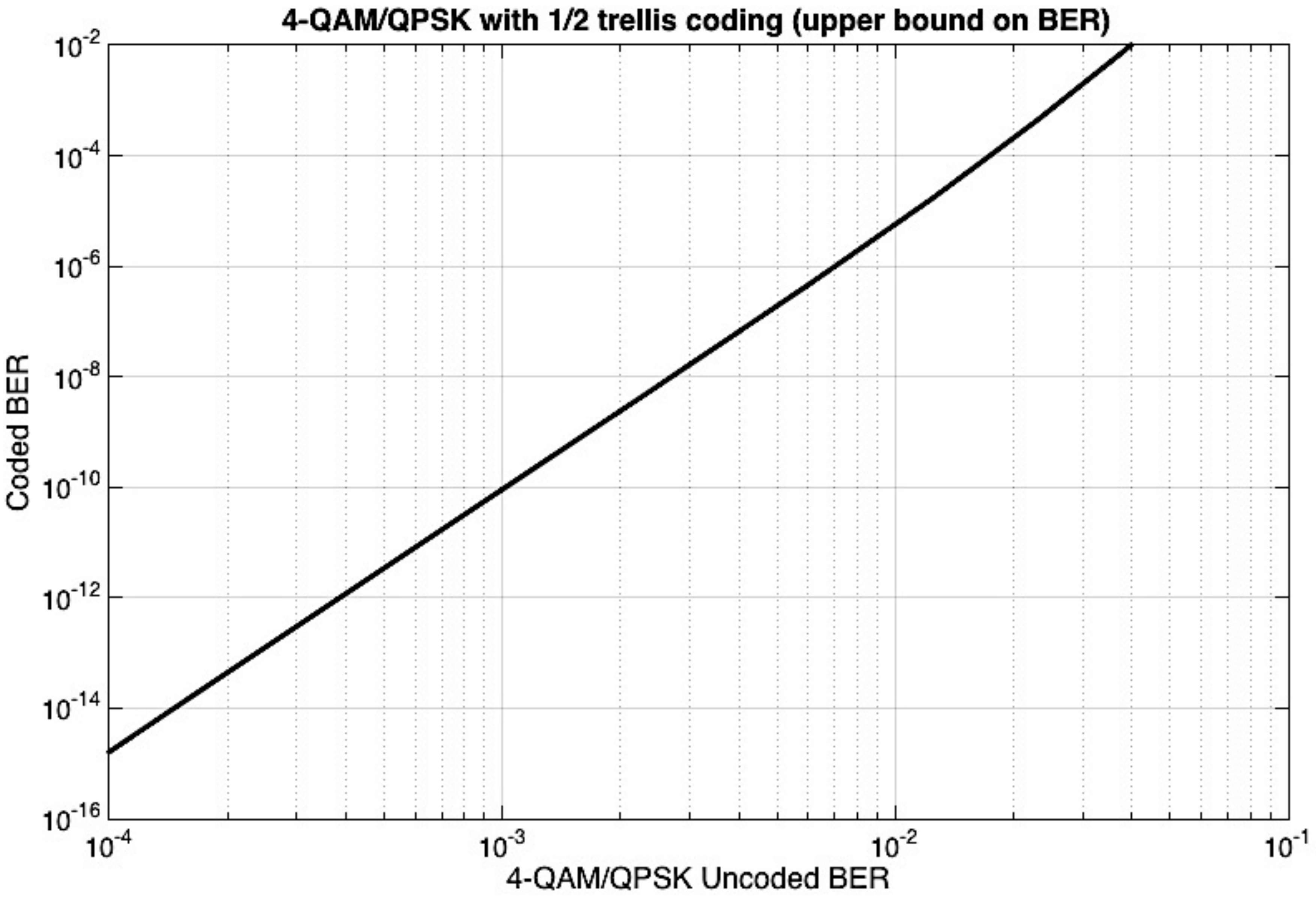
$$R^{opt} = \left[Id^{(KxK)} \operatorname{var}\left(w_k\right) + G \right]^{-1}$$

Multi-user detection for multi-beam satellites (3)

- **Drawbacks of theoretical MUD algorithms**
  - **The proposed analysis is useful to understand advantages and limitations of MUD in multi-beam satellites. However, theoretical ML and theoretical MMSE are not suitable for practical applications;**
  - **The computational burden of ML becomes unaffordable for high values of *K* (and *M*) (*NP-complete* problem);**
  - **Just a numerical example: for *K*=10 interfering signals with 16-level modulation, we have $N_s=2^{40}$=1,099,511,627,776 symbol combinations to test during a symbol period!**
  - **But also Wiener solution of MMSE is difficult to be obtained! *KxK* matrix inversion can be easily computed on a PC with MATLAB, but not on a real DSP device! Moreover, the operation may become unfeasible if the matrix *G* is "almost singular."**

Simulation strategy and results

- **Simulation setup**
  - Simulations in **MATLAB environment**;
  - **QPSK modulation is adopted** with ½ trellis coding.
  - The performance of trellis coding is appreciated "off-line" by **measuring the simulated channel BER** and using the following curve aside that draws the upper bound of BER after Viterbi decoding vs. channel (uncoded) BER:



Curve obtained by using "BERTOOL" functions of MATLAB

10^{-11} coded BER is required for high quality HDTV broadcasting and/or efficient Satellite-TCP-based services -> channel BER should be less or at most equal to $6 \cdot 10^{-4}$

Simulation parameters

- **TX/RX configuration and interference parameters**
  - **Users are supposed to be at the center of their spotbeam. This implies that:**

$$\theta_{ii} = 0^\circ \quad \theta_{ij} = \theta_{ji} \quad \forall i, j$$

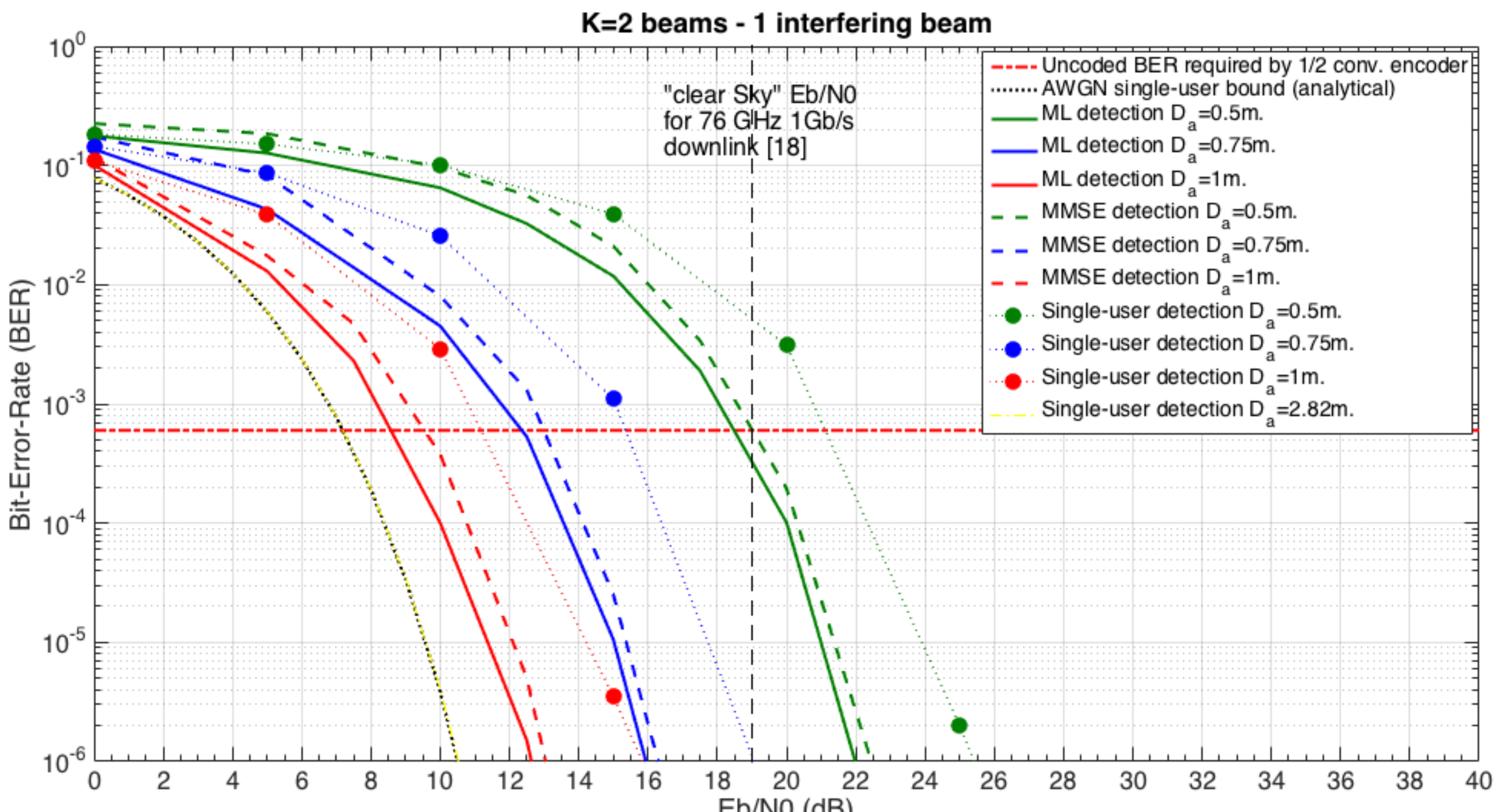
  - **The relative distances of the receivers served by the interfering spot beams are in the order of some hundreds of kilometers. In the following, the *C/I* matrix (values in dB) is given for various numbers of users and antenna diameters:**

	K=2	*K=3*	*K=6*
D_a=0. 5m.	1.69dB	-1.37dB	-5.16dB
D_a=0.75m.	3.89dB	0.84dB	-3.0dB
D_a=1m.	7.2dB	3.98dB	-0.055dB
$D_a=2\sqrt{2}$ m.	48.57dB	40.58dB	39.24dB

For D_a=2.82 m. (value considered in[4] for a 20GHz antenna), we don't need any kind of MUD, but the use of such big antennas is not realistic in commercial applications.

Simulation results

- **Channel (uncoded) BER: K=2 users (1 wanted + 1 interfering)**



$$Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \le P_e^{mu} \le Q\left(\left[\frac{1}{2}\left(\frac{I}{C}\right)+\frac{N_0}{2E_b}\right]^{-1/2}\right)$$

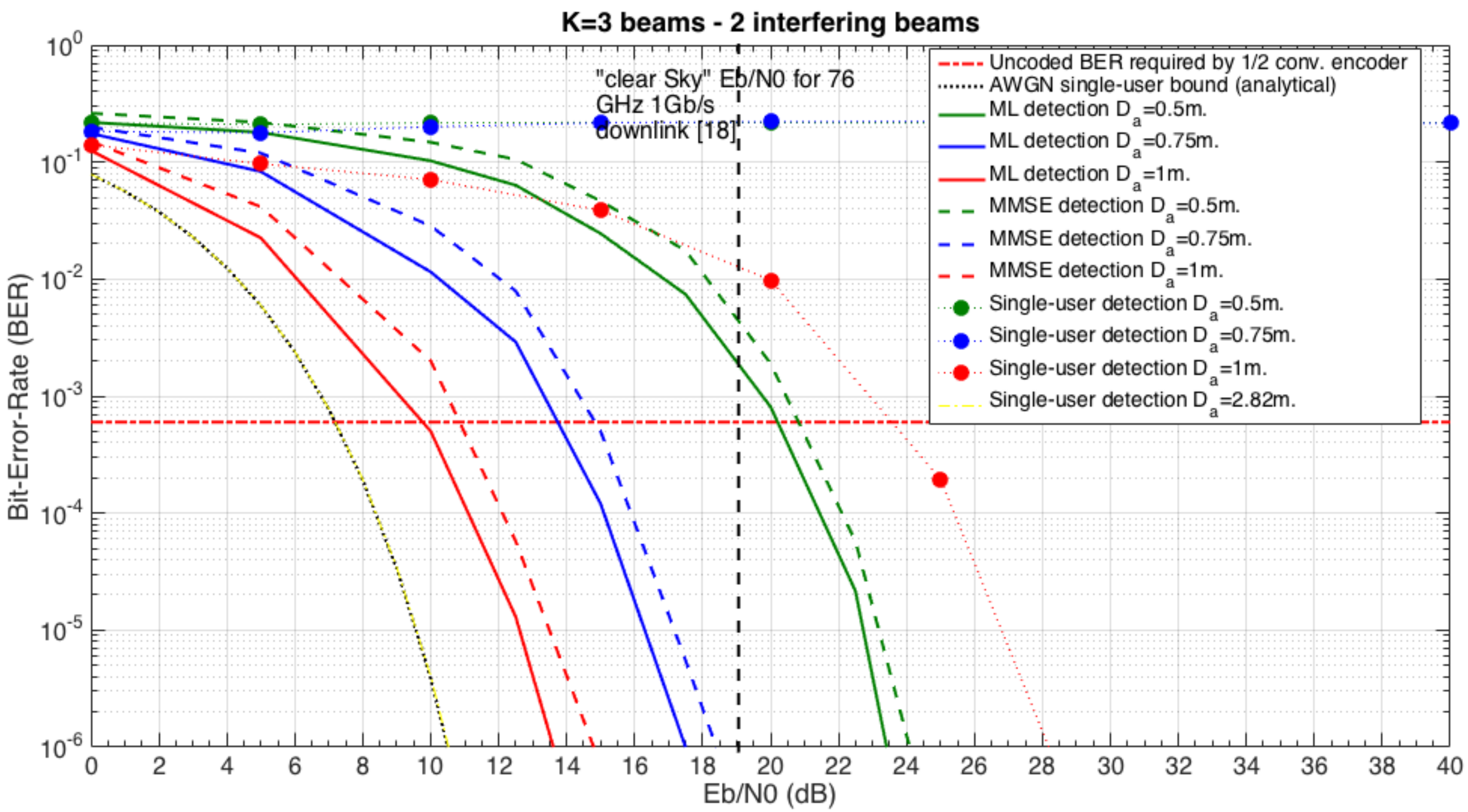
Lower bound: <u>QPSK AWGN BER</u>, upper bound: <u>single-user detection</u> (no MUD);

Theoretical ML and MMSE are almost overlapped. Single-user detection is not so far from MUD performance;

Margin for supplementary (atmospheric) attenuations available for larger antenna diameters.

Simulation results

- **Channel (uncoded) BER: K=3 users (1 wanted + 2 interfering)**

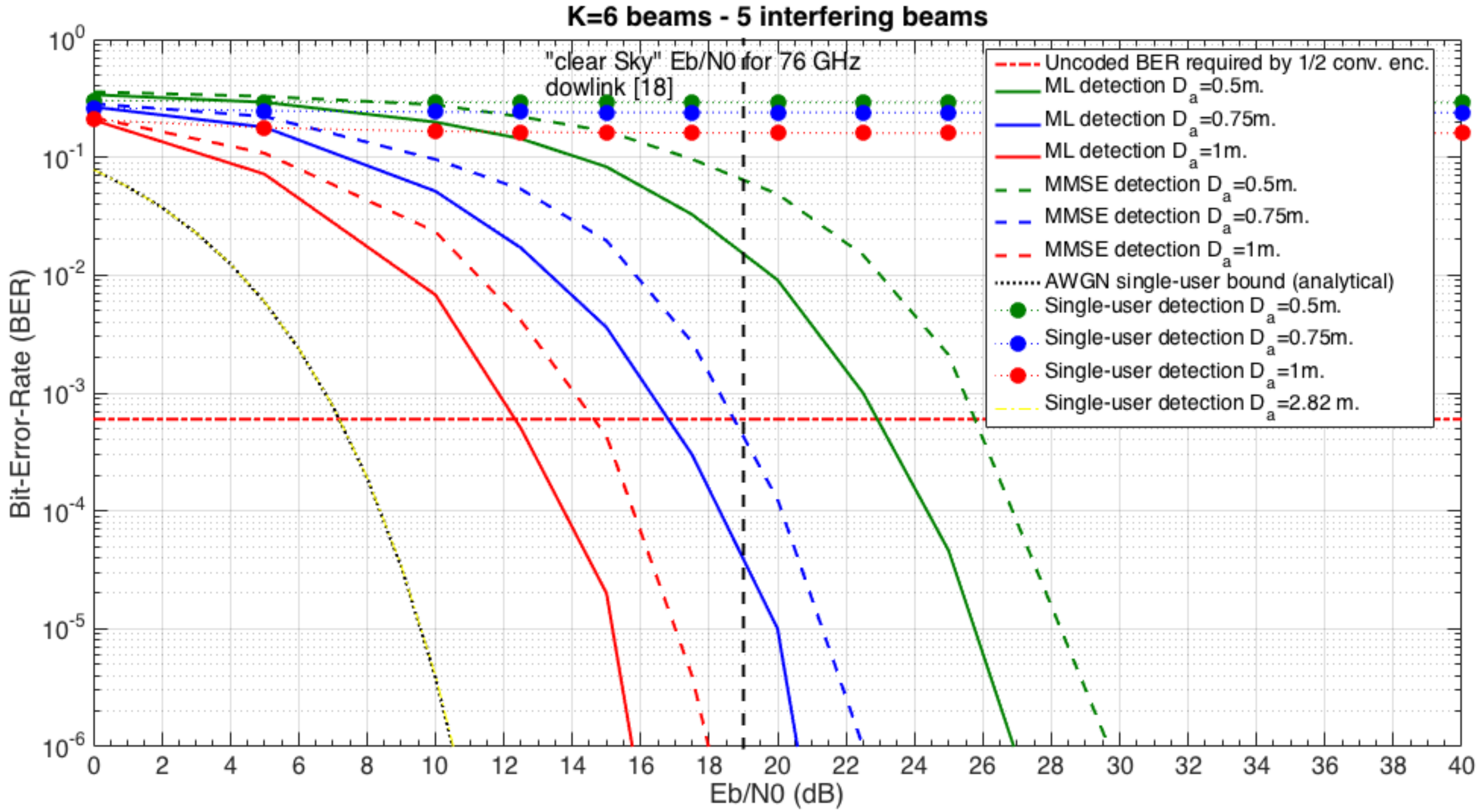


Theoretical ML and MMSE are still close, but farer from lower bound. Single-user detection badly works when antennas have reasonable diameters;

The margin for supplementary attenuations decreases.

Simulation results

- **Channel (uncoded) BER: K=6 users (1 wanted + 5 interfering)**



MMSE is evidently suboptimal; all BER curves are going farer and farer from the single-user bound;

Some margin for supplementary attenuations (around 7dB) is available only if antennas of 1m of diameter are used

From MUD performance assessment to MUD practical implementation

- **ML-MUD practical implementation**

  - **The objective of state-of-the-art methodologies is to reduce the (enormous) search space and to find a good sub-optimal solution;**

  - **In literature, we can find:**
    - **Neural network-based approaches[7];**
    - **Sphere decoding of lattice structures[8];**
    - **Maximum-A posteriori-Probability (MAP) detectors, based on the application of ML MUD to restricted sets of bits of a coded bit-stream[9];**
    - **Genetic Algorithm (GA)-assisted ML detection and other biology-inspired optimization algorithms[10]**

From MUD performance assessment to MUD practical implementation

- **MMSE-MUD practical implementation**

  - **The objective of state-of-the-art methodologies is to avoid the direct inversion of the matrix;**

$$P = \left[Id^{(KxK)} \operatorname{var}(w_k) + G \right]$$

  - **In literature, we can find:**

    - **Iterative optimization methodologies based on gradient descent, namely: Least-Mean Square (LMS) and Recursive-Least Square (RLS), computationally efficient, but the convergence to optimal MMSE solution may be slow[6];**

    - **Genetic Algorithm (GA)-assisted MMSE: efficient in converging to optimal solution, but computationally-demanding[11]**

From MUD performance assessment to MUD practical implementation

- **Serial or parallel interference cancellation (SIC, PIC)**
  - **It is possible, provided the knowledge of channel matrix, to reconstruct multi-user interference and subtract it iteratively from the wanted signal[12];**
  - **In literature, serial interference cancellation (SIC) and parallel interference cancellation (PIC) have been proposed;**
  - **Interference cancellation is computationally affordable, but it may have serious convergence problems, if the first iteration (single-user detection) provides a lot of symbol errors.**

Conclusion and future work

- Conclusion
  - Multi-user detection is essential to improve multi-beam satellite performance when aggressive frequency reuse is employed to boost spectral efficiency;
  - In a broadband EHF multi-beam scenario, like the one considered in our work, multi-user detection should be combined with efficient antenna systems characterized by conveniently-reduced sidelobe levels;
  - ML-MUD performs better than MMSE-MUD if the number of interfering beams increases. However, ML-MUD becomes computationally intractable for high number of users;
  - If few beams interfere the wanted signal, MMSE-MUD performs very close to optimum;
  - Both ML and MMSE MUD should be implemented with realistic signal processing algorithms that can be afforded by real-world HW/SW architectures.

Conclusion and future work

- **Future work**

  - **The design of satellite antenna systems characterized by reduced diameters and high capability of reducing interference in the spatial domain is a must for broadband multi-beam satellites (the SFBN system considered in this work does not cope with such requirements);**

  - **The practical implementation of multi-user detection algorithms (ML, MMSE, PIC, SIC, etc.) should be implemented by carefully considering the constraints of signal processing architectures working at earth terminal level.**

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Biography and contact informations

Cosimo Stallo *graduated in Electronic Engineering at Polytechnic of Bari in 2005. He received a MSc Degree cum laude in "Advanced Communication and Navigation Satellite Systems" in 2006 at the University of Rome "Tor Vergata". He received a PhD degree in Microwave and Telecommunications in 2010 at University of Rome Tor Vergata. Since February 2010 he has been the Chair of the IEEE AESS Space Systems Panel. He is currently a senior researcher at Consortium RadioLabs. His main fields of research concern space communications and navigation systems, and millimeter wave communications. He is the author of about 50 papers on international journals/transactions and proceedings of international conferences.*

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Claudio Sacchi *received the "Laurea" Degree in Electronic Engineering, and the Ph.D. in Space Science and Engineering at the University of Genoa (Italy) in 1992 and 2003, respectively. Since August 2002, Dr. Sacchi is assistant professor at the Faculty of Engineering of the University of Trento (Italy). Claudio Sacchi is author and co-author of more than 90 papers published in international journals and conferences. In 2011, he was guest editor of the special issue of PROCEEDINGS OF THE IEEE: "Aerospace Communications: History, Trends and Future." The research interests of Dr. Sacchi are mainly focused on wideband mobile and satellite transmission systems based on space, time and frequency diversity; MIMO systems; array processing; multi-rate and multi-access wireless communications; EHF broadband aerospace communications; software radio and cognitive radio; radio communications for emergency recovery applications. Claudio Sacchi is a senior member of IEEE and a member of the IEEE ComSoc, and the IEEE AESS society.*

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