Noncoherent Communications for Next-Generation Wireless Systems

Indo-French Seminar
6G Wireless Networks: Challenges and Opportunities

CEFIPRA

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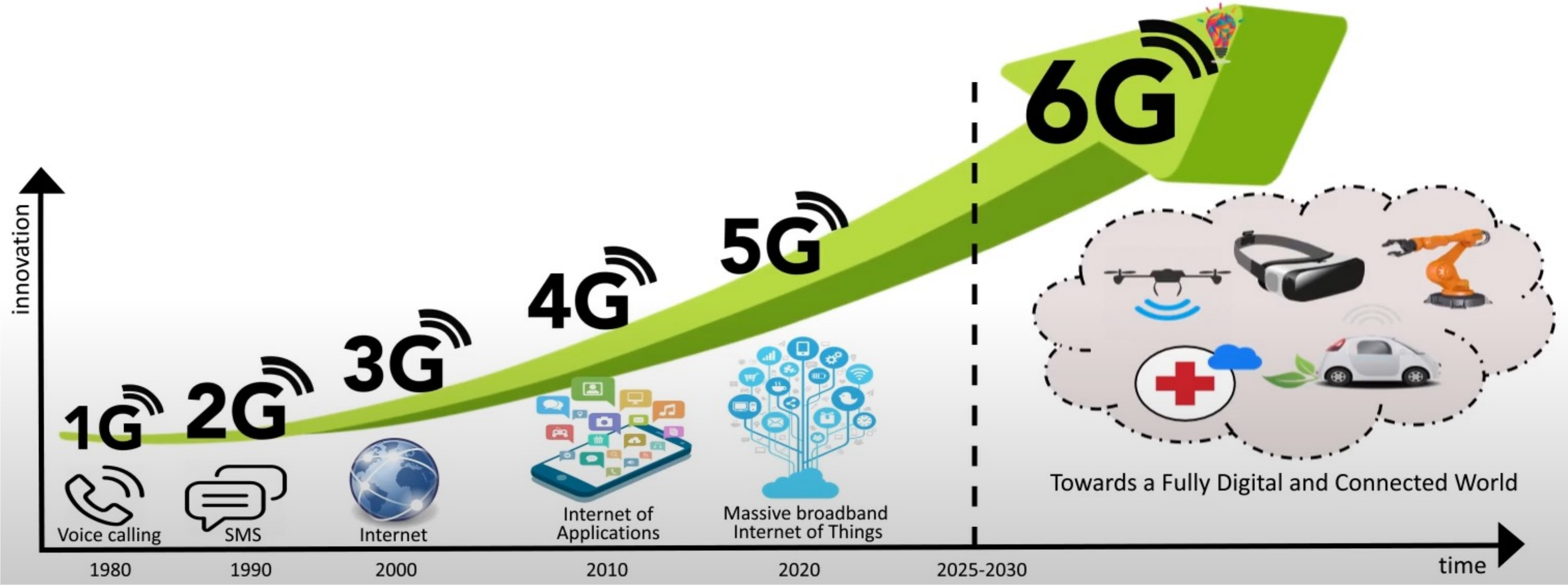
Introduction

- While the deployment of 5G networks is still ongoing globally, research has started to explore emerging technologies and services, defining new requirements, and identifying disruptive enabling technologies
- The rapid development of **data-centric** and **automated processes** may exceed even the capabilities of emerging 5G systems, thereby calling for a new wireless generation



Toward 6G Networks: Use Cases and Technologies, IEEE Communications Magazine, vol. 58, no. 3, pp. 55-61, March 2020.

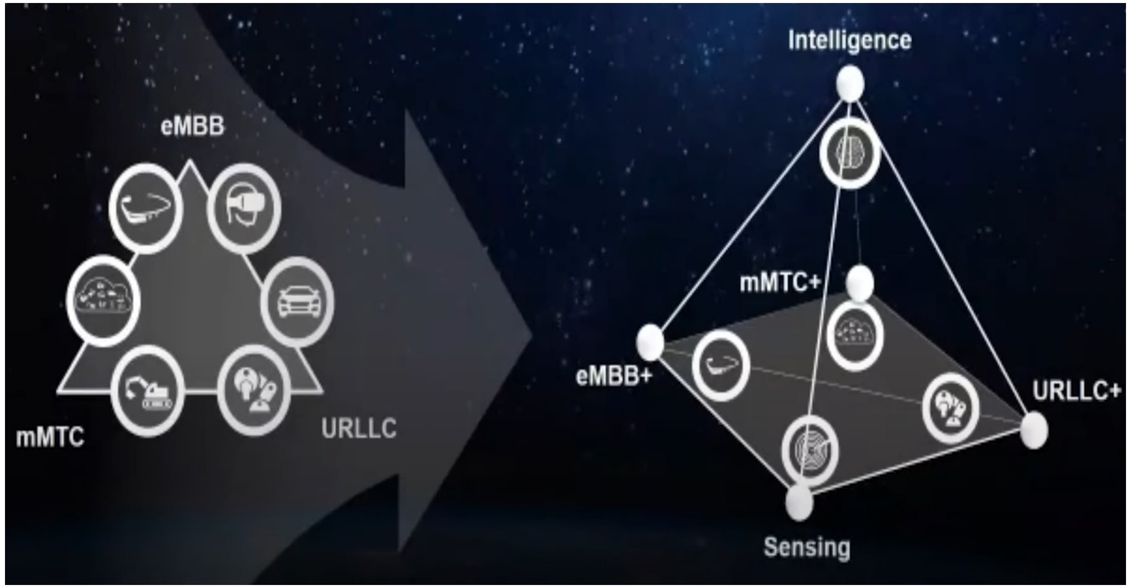
From 5G to 6G

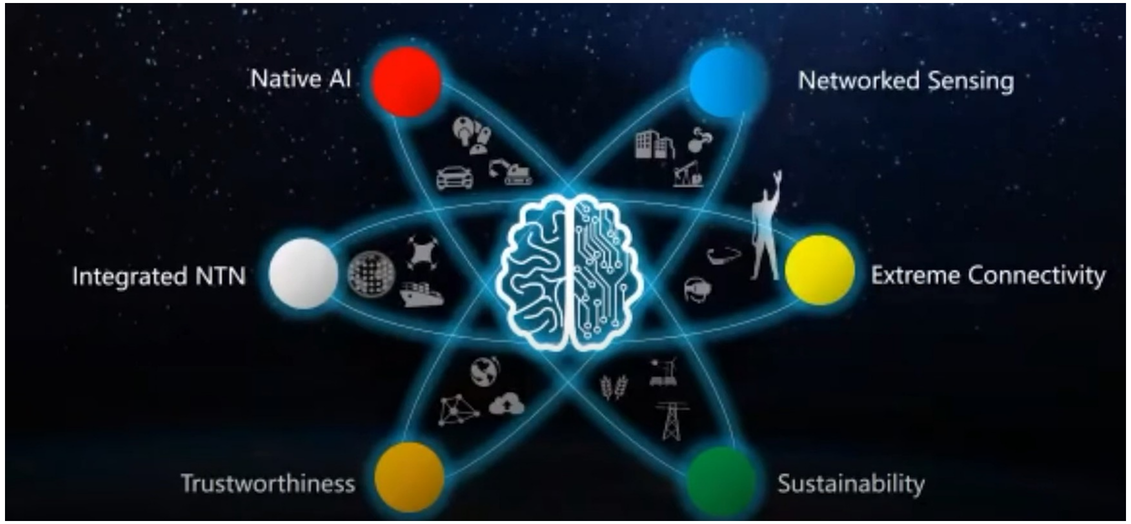
Main pillars of 5G:

- Enhanced mobile broadband (emBB):
  - Services requiring fast connections and high data rates such as video streaming and AR/VR
  - Static scenario: Downlink (20 GBbs); Uplink (10 GBps)
  - Mobility scenarios: Downlink (100 Mbps); Uplink (50 Mbps)
- Ultra-reliable low-latency communication (URLLC):
  - Targets 1 ms latency
  - Supports mission-critical applications such as autonomous driving and remote robotic surgery
- Massive machine type communications (mMTC):
  - Deployment of 1 Million devices/km^2
  - Requires lo-cost, low-power and long-range devices

Key Technologies of 5G:

- Massive MIMO
- Use of mmWave frequencies
- Network functions virtualization (NFV) relying on replacing network hardware with virtual machines
- Mobile edge computing (MEC) to process in real-time large amounts of data produced by edge devices
- Device-to-device (D2D) communications
- Software-defined networking (SDN)





5.5G features:

- Uplink centric broadband communication (UCBC):
  - Services massive things with broadband abilities such as HD video uploading and machine vision
- Real-time broadband communication (RTBC):
  - Combines broadband features with high reliability such as extended reality applications and holograms
- Integrated sensing and communications (ISAC):
  - Integrates both communications and sensing capabilities in applications like positioning, spectroscopy, and imaging

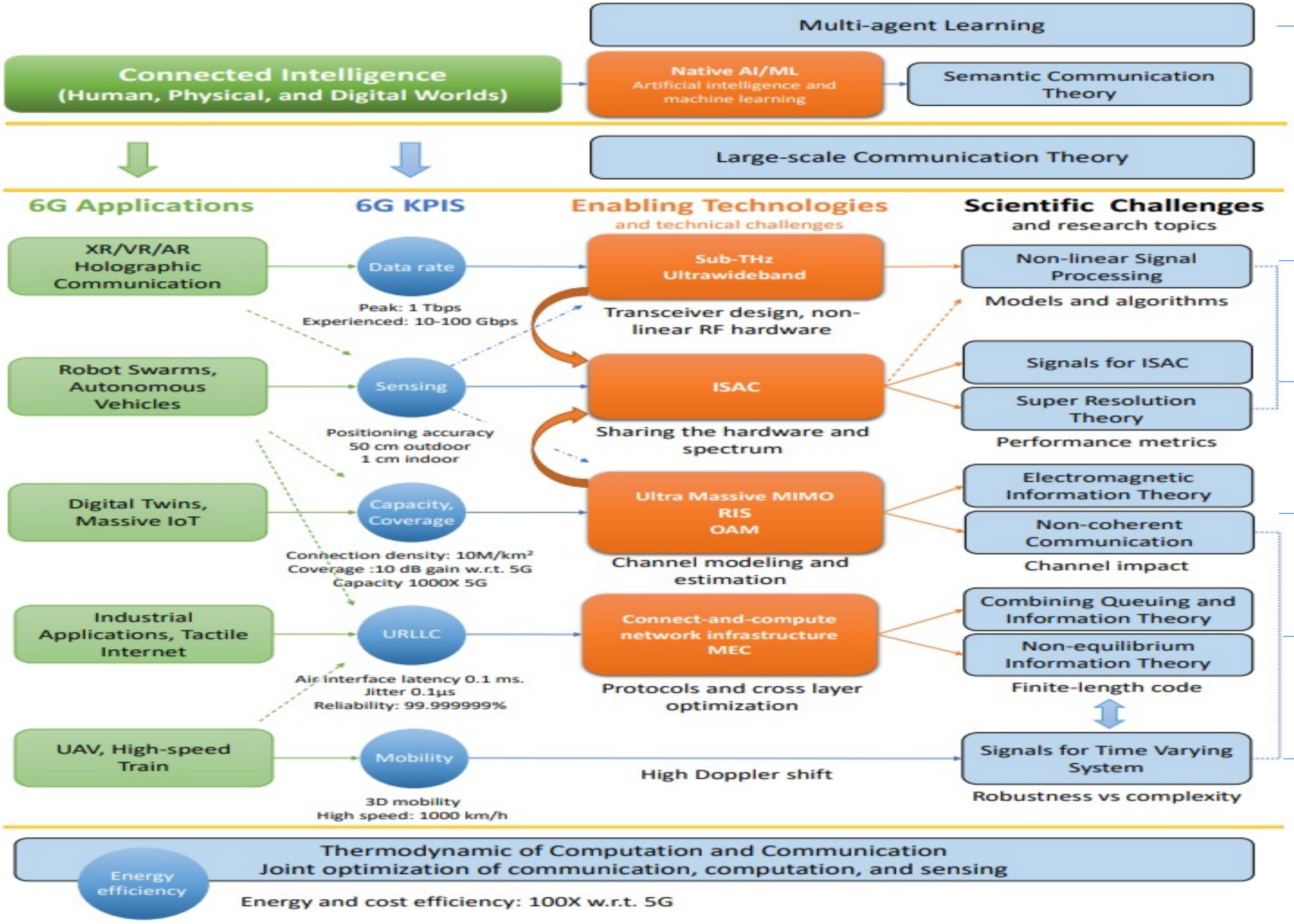
6G: Connected Intelligence:

- Extremely immersive experiences
- Haptics
- Industry 4.0 with connected intelligence
- 3D full coverage of the earth
- Native artificial intelligence (AI)-empowered wireless communication
- Fog computing

6G Use Cases

Toward 6G Networks: Use Cases and Technologies, IEEE Communications Magazine, vol. 58, no. 3, pp. 55-61, March 2020.

Synergy between 6G Scientific Challenges



Multiple Smart entities connected

How they talk: Collection of massive data, exchange of representation with other agents, taking actions, and receive feedback from environment

Non-linear hardware models and low-complexity algorithms signal processing algorithms required

Design of joint waveforms, super-resolution parameter estimation

Accurate channel model and estimation of channels for large number of antennas

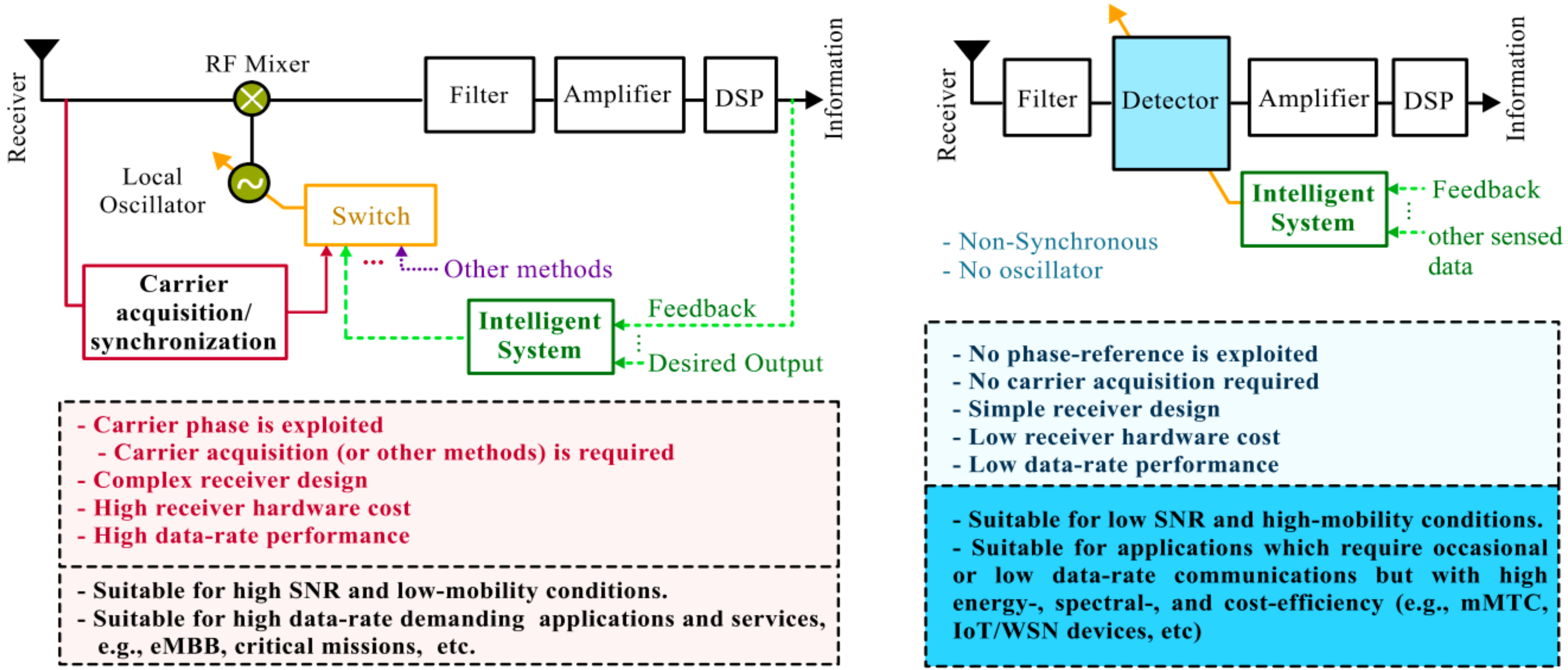
Time sensitive processing and AI technologies at network edges

Signal designs to tackle high Doppler shifts

Twelve Scientific Challenges for 6G: Rethinking the Foundations of Communications Theory, https://doi.org/10.48550/arXiv.2207.01843.

Noncoherent Communications

Coherent versus Noncoherent Communications



(a) Coherent Receiver

(b) Non-Coherent Receiver (intelligent)

Coherent versus Noncoherent Communications

Coherent communications

- Coherent communication needs channel state information for reliable data transmission
- Various system parameters, including multipath propagation and frequency offsets, introduce significant challenges to accurately estimating phase and timing
- Coherent systems have to employ local oscillators, mixers, and phase synchronization circuitry to obtain the accurate CSI
- These components contribute to increased hardware complexity in the transceiver architecture as they aim to compensate for the adverse effects of the physical communication system
- Acquisition of perfect CSI is challenging when the carrier frequencies are high and high mobility scenarios
- Further, channel estimation complexity increases with the number of transmit and receive antennas

Non-coherent communications

- Noncoherent communication does not require precise synchronization of carrier phases between the transmitter and receiver
- Its counterpart coherent communication maintains phase coherence between the two ends for reliable data transmission
- However, in real-world scenarios, various factors like fading, Doppler shifts, and frequency instability can cause phase variations, making it challenging to maintain coherent synchronization
- Noncoherent communication is primarily concerned with extracting information from the amplitude and frequency characteristics of the received signal, without attempting to recover the carrier phase
- This approach makes noncoherent communication more resilient to phase variations and fluctuations in the communication channel
- Instead of relying on precise phase alignment, noncoherent systems capitalize on the statistical properties of the signal

Challenges and Limitations

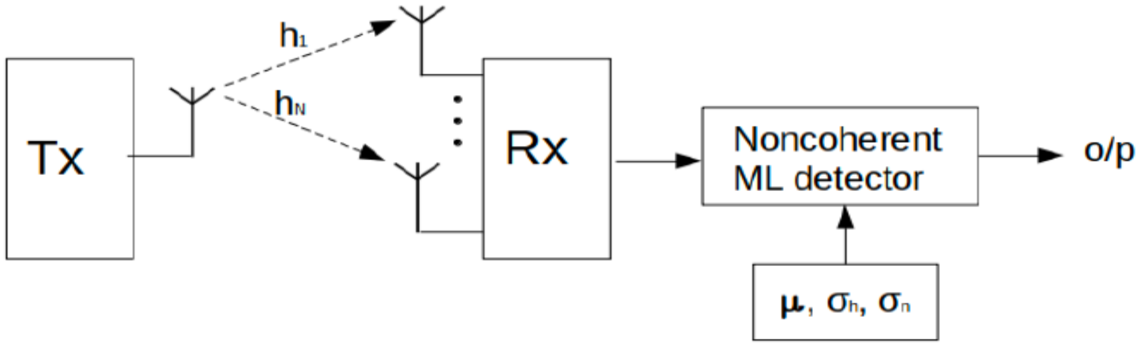
- **Higher Error Rates:**
  - Noncoherent communication typically experiences higher bit error rates compared to coherent systems due to the lack of precise phase information
- **Reduced Capacity:**
  - Noncoherent communication have limitations in terms of achievable data rates and capacity due to its reliance on amplitude and frequency information
- **Lower Spectral Efficiency:**
  - Noncoherent systems often require wider bandwidth to achieve the same level of performance as coherent systems. This reduced spectral efficiency can be a limiting factor in bandwidth-constrained scenarios
- **Complexity of Modulation Schemes:**
  - Noncoherent communication schemes, such as FSK or ASK, are simpler to implement but may not be as efficient as more complex modulation schemes in terms of spectral efficiency and error performance

Mitigation Strategies

- **Diversity Techniques:**
  - Diversity reception involves using multiple antennas or paths to improve signal reliability by reducing the impact of fading and variations
- **Error Correction Coding:**
  - The use of error correction codes can help improve the overall system's reliability by correcting errors introduced during transmission

Optimal multi-level ASKs for noncoherent SIMO wireless system

- A noncoherent SIMO wireless system is considered



- The received symbol at the ℓ-th diversity branch is given as

$$r_\ell = h_\ell x + n_\ell, \;\; h_\ell \sim \mathcal{CN}\left(\mu_\ell, \sigma_h^2\right), \;\; n_\ell \sim \mathcal{CN}\left(0, \sigma_n^2\right), \; \ell = 1, \ldots, N$$

- x is the transmitted information-bearing symbol
  1. *One-sided ASK:*

$$x_m = \sqrt{E_{x_m}}, \;\; m = 1, \ldots, M, \sqrt{E_{x_m}} < \sqrt{E_{x_{m+1}}}, \; \forall m \in \{1, \ldots, M-1\}$$

  2. *Two-sided ASK:*

$$x_m \in \left\{-\sqrt{E_{\frac{M}{2}}}, \ldots, -\sqrt{E_1}, \sqrt{E_1}, \ldots, \sqrt{E_{\frac{M}{2}}}\right\}$$

System Model

- A noncoherent detection scheme is used at the receiver
- The optimal noncoherent ML detector is employed which searches for x that maximizes the log-likelihood function $\ln\{f(\mathbf{r}|_x)\}$

$$\widehat{x} = \arg\max_{x\in\chi} \ln\{f(\mathbf{r}|_x)\}, \quad \chi = \{x_m, \; m = 1, \ldots, M\}$$

- The received symbol vector $\mathbf{r}$ conditioned on x follows the complex Gaussian distribution

$$f(\mathbf{r}|_x) = \frac{1}{\pi^N \left(|x|^2\sigma_h^2 + \sigma_n^2\right)^N} \exp\left\{-\frac{(\mathbf{r}-\boldsymbol{\mu}x)^H(\mathbf{r}-\boldsymbol{\mu}x)}{|x|^2\sigma_h^2+\sigma_n^2}\right\}$$

- The simplified decision rule of the optimal noncoherent receiver

$$\widehat{x} = \arg\min_{x\in\chi} N\ln\left(|x|^2\sigma_h^2 + \sigma_n^2\right) + \frac{\|\mathbf{r}-\boldsymbol{\mu}x\|^2}{|x|^2\sigma_h^2+\sigma_n^2}$$

Error Analysis

- General expression for union-bound on SEP

$$P_e \leq \frac{1}{M}\sum_{i=1}^{M}\left[\sum_{\substack{j=1,\\ B_i>B_j}}^{M}\sum_{k=0}^{\infty}\left(\frac{e^{-\lambda_{ij}}\lambda_{ij}^{k}}{k!}-\sum_{p=0}^{N+k-1}\frac{e^{-\lambda_{ij}-\alpha_{ij}}\lambda_{ij}^{k}\alpha_{ij}^{p}}{k!p!}\right)\right.$$

$$\left.+\sum_{\substack{j=1,\\ B_i<B_j}}^{M}\sum_{k=0}^{\infty}\sum_{p=0}^{N+k-1}\frac{e^{-\lambda_{ij}-\alpha_{ij}}\lambda_{ij}^{k}\alpha_{ij}^{p}}{k!p!}+\sum_{\substack{j=1,j\neq i\\ B_i=B_j}}^{M}Q\left(\sqrt{\frac{2NK_{av}\Gamma_i}{\Gamma_i+NK_{av}+1}}\right)\right]$$

- Closed-form expression for union-bound on SEP for large N

$$P_{e|N\gg 1} \leq \frac{1}{M}\sum_{i=1}^{M}\left[\sum_{\substack{j=1,\\ B_i>B_j}}^{M}1-Q\left(\frac{\alpha_{ij}-(N+\lambda_{ij})}{\sqrt{N+2\lambda_{ij}}}\right)+\sum_{\substack{j=1,\\ B_i<B_j}}^{M}Q\left(\frac{\alpha_{ij}-(N+\lambda_{ij})}{\sqrt{N+2\lambda_{ij}}}\right)\right.$$

$$\left.+\sum_{\substack{j=1,j\neq i\\ B_i=B_j}}^{M}Q\left(\sqrt{\frac{2NK_{av}\Gamma_i}{\Gamma_i+NK_{av}+1}}\right)\right],$$

$$\lambda_{ij}=\frac{B_i\,||\widetilde{\boldsymbol{\mu}}||^2}{(B_i-B_j)^2},\quad \alpha_{ij}=\frac{NB_j}{B_i-B_j}\ln\frac{B_i}{B_j}+\frac{B_j}{(B_i-B_j)^2}\,||\widetilde{\boldsymbol{\mu}}||^2,\quad B_i=|x_i|^2\sigma_h^2+\sigma_n^2,\quad \Gamma_i=\frac{|x_i|^2\left(||\boldsymbol{\mu}||^2+\sigma_h^2\right)}{\sigma_n^2}$$

Optimization of ASK Modulation Schemes

- The optimization framework can be expressed in terms of $\Gamma_m, \quad m = 1, \ldots, M$ and Γ_{av}, as

$$\min_{\Gamma_1, \ldots, \Gamma_M} P_e$$

$$\text{s.t.} \sum_{m=1}^{M} \Gamma_m = M\Gamma_{av}$$

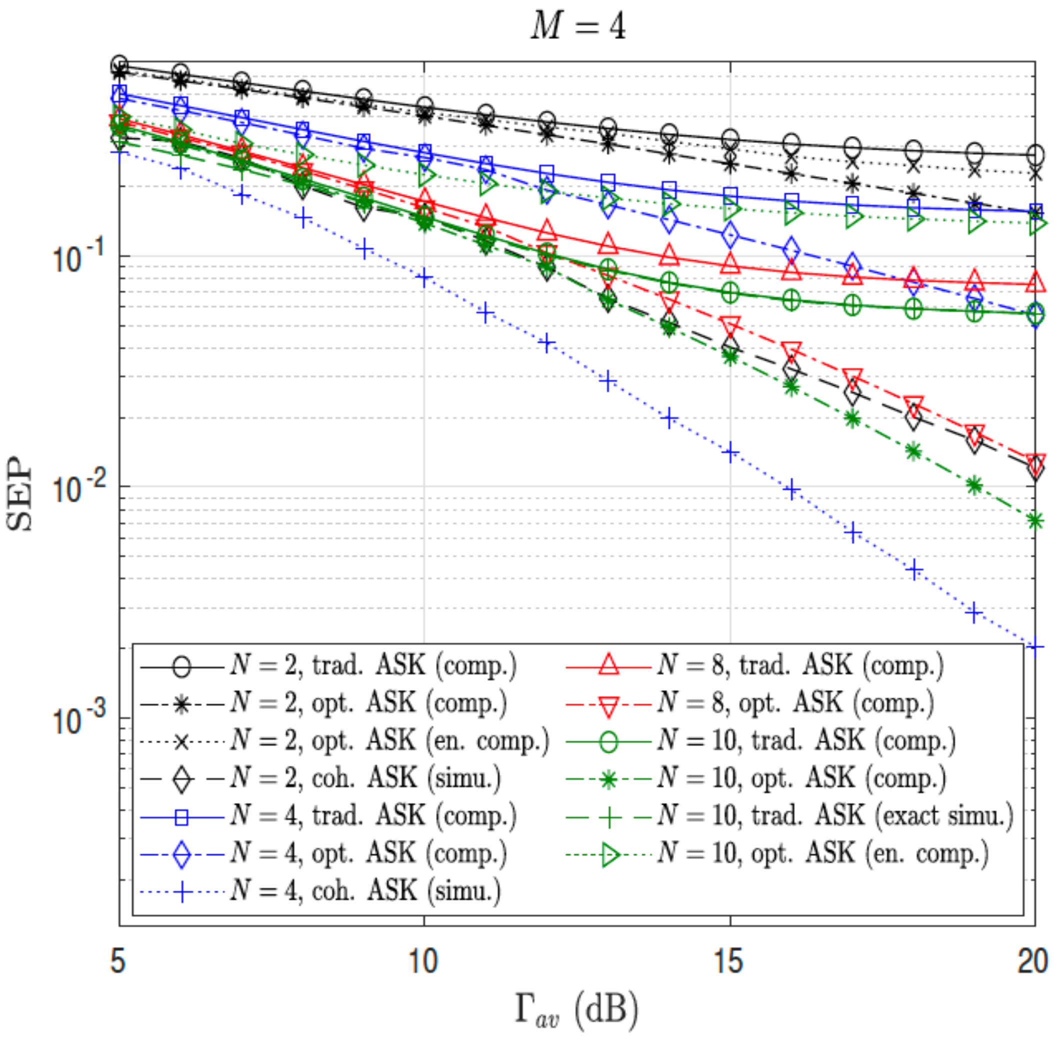
- The constrained optimization problem can be solved using the Lagrangian multiplier technique

$$\mathcal{L}\left(\Gamma_1, \ldots, \Gamma_M, \Lambda\right) = P_e + \Lambda\left(\sum_{m=1}^{M} \Gamma_m - M\Gamma_{av}\right)$$

- The optimal SNR values are denoted by $\Gamma_{m,opt}, \quad m = 1, \ldots, M$, can be obtained by simultaneously solving the expressions as

$$\frac{\partial\mathcal{L}\left(\Gamma_1, \ldots, \Gamma_M, \Lambda\right)}{\partial\Gamma_m} = 0\,, \; m = 1, \ldots, M\,, \; \frac{\partial\mathcal{L}\left(\Gamma_1, \ldots, \Gamma_M, \Lambda\right)}{\partial\Lambda} = 0$$

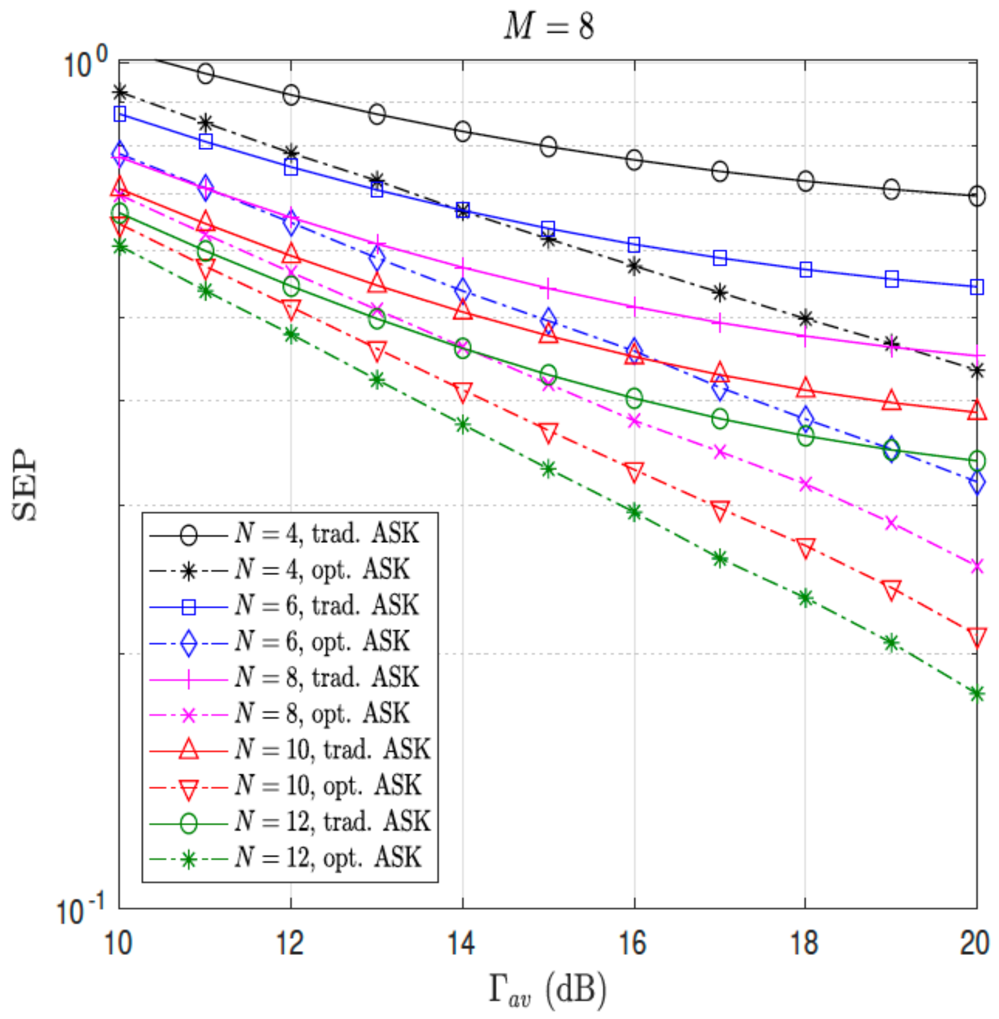
Numerical Analysis with One-sided ASK



SEP versus average SNR per symbol per branch

- Comparison of the performance of the optimal one-sided ASK constellation is provided with the traditional one-sided ASK and a SIMO noncoherent receiver based on the energy of the received symbols
- The performance of the optimal one-sided ASK is superior as compared to the traditional one-sided ASK
- The SEP values of the system for the traditional ASK tend to saturate at higher SNR values
- Higher diversity order is achieved with the optimal modulation scheme
- The gap between the bound on SEP and the actual simulated SEP plot is reduced with an increase in SNR
- Coherent pilot-based ASK modulation scheme outperforms the noncoherent case
- Optimal ML outperforms the energy-based receiver structure

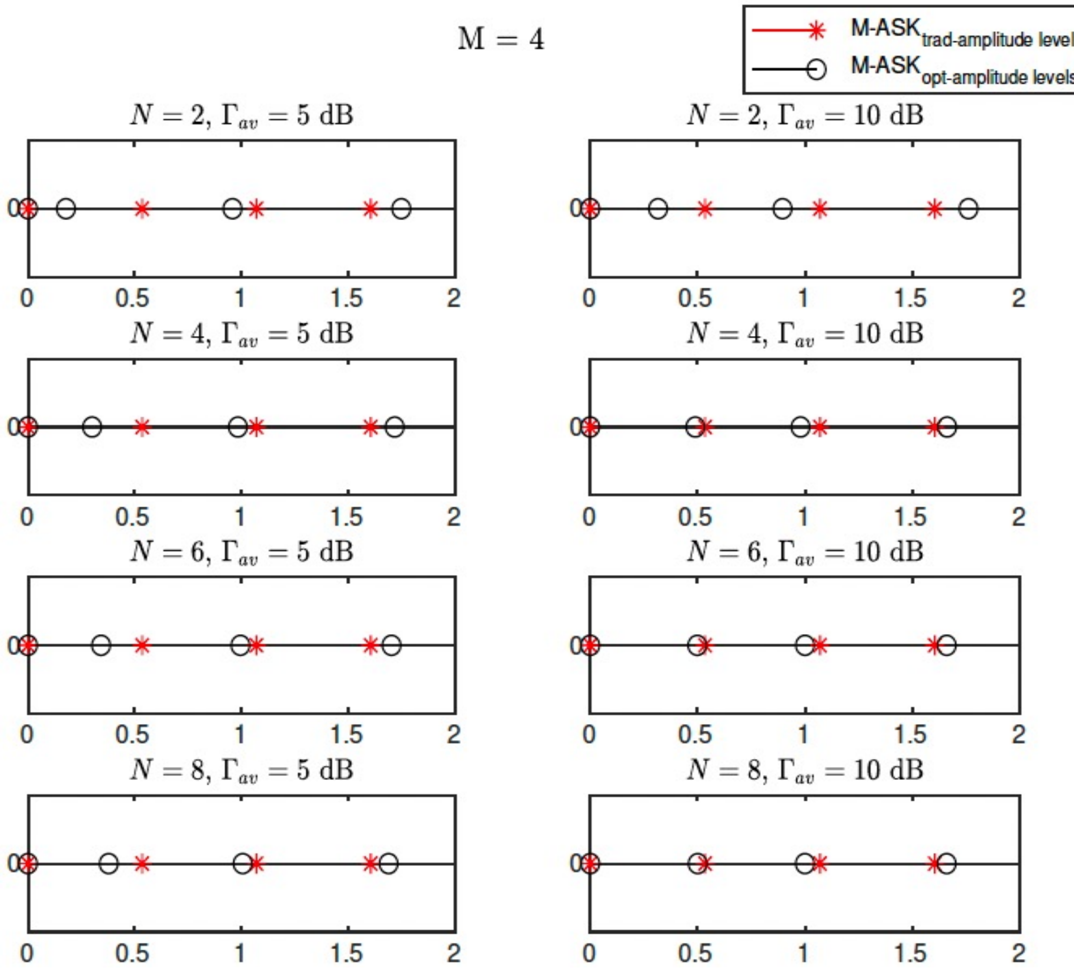
Numerical Analysis with One-sided ASK



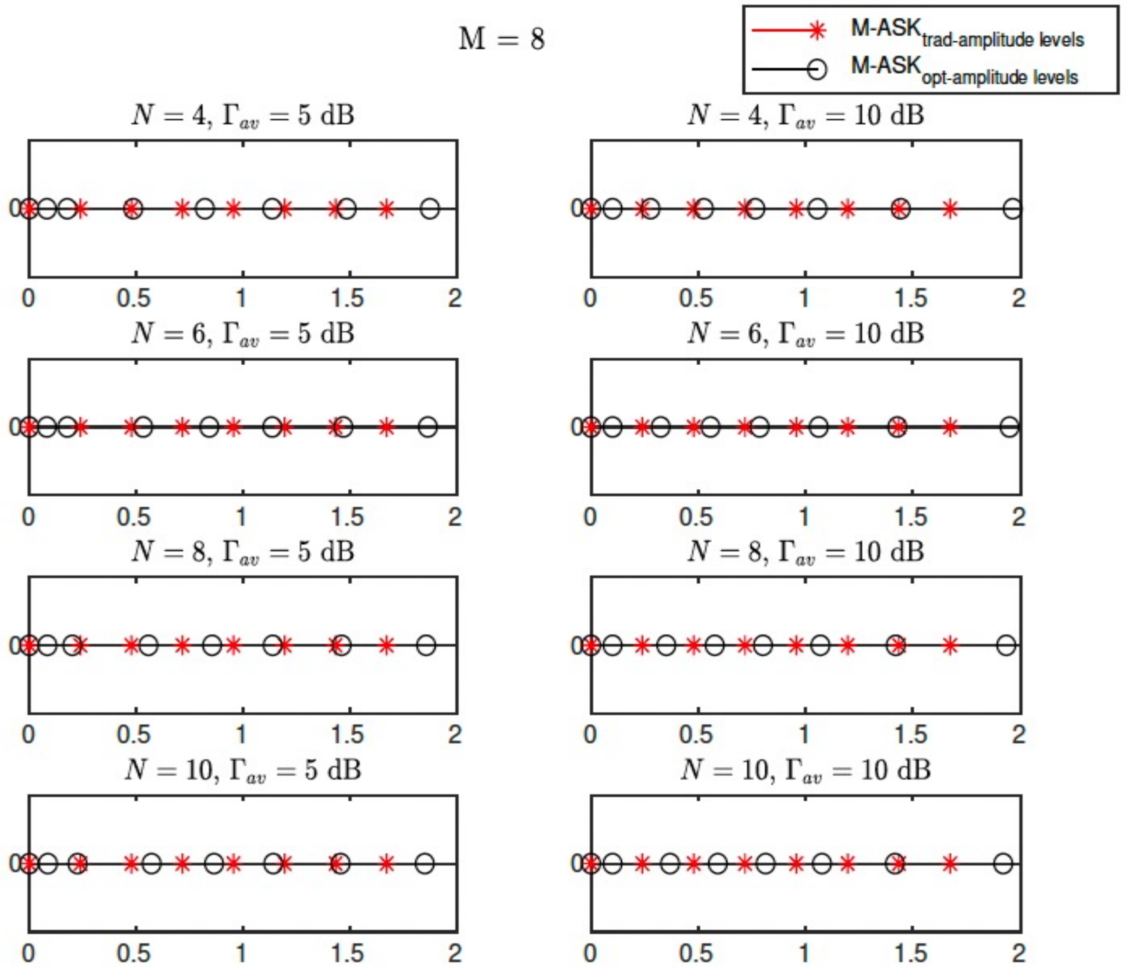
SEP versus average SNR per symbol per branch

- Comparison of the performance of the optimal one-sided 8-ary ASK constellation is provided with the traditional one-sided ASK
- The performance of the optimal one-sided ASK is superior as compared to the traditional one-sided ASK
- The SEP values of the system for the traditional ASK tend to saturate at higher SNR values
- Higher diversity order is achieved with the optimal modulation scheme

Numerical Analysis with One-sided ASK

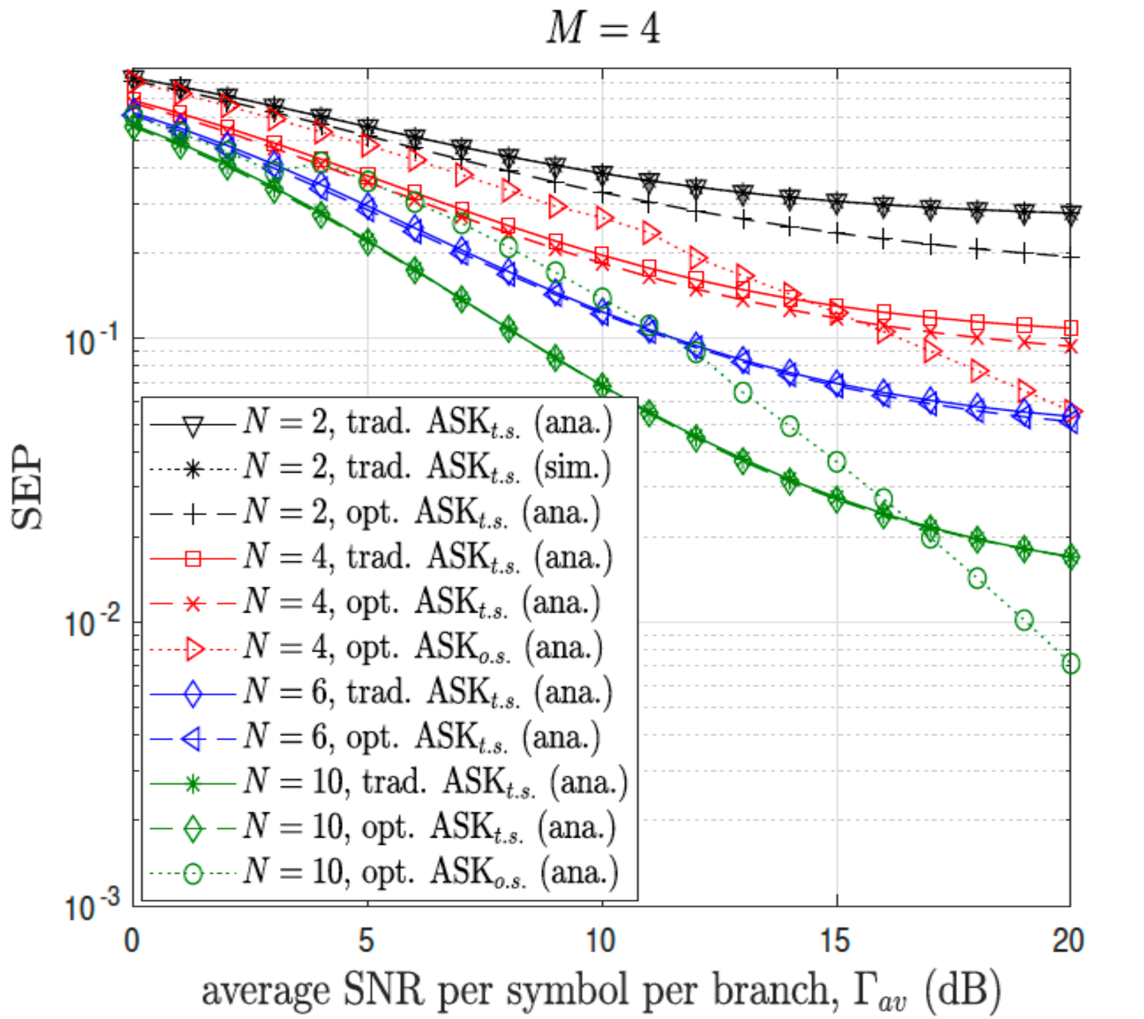


Traditional and optimal 4-ary ASK constellation diagrams

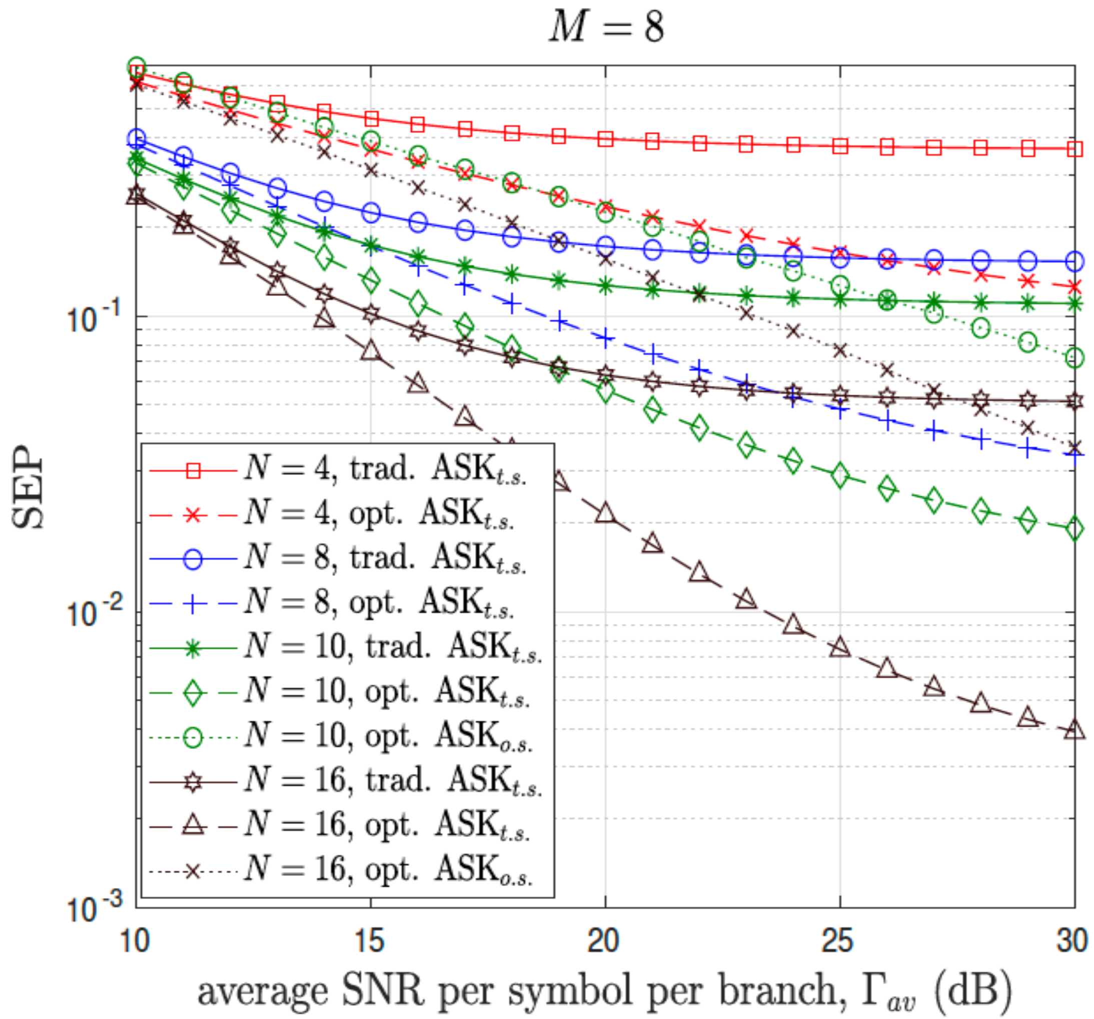


Traditional and optimal 8-ary ASK constellation diagrams

Numerical Analysis with Two-sided ASK

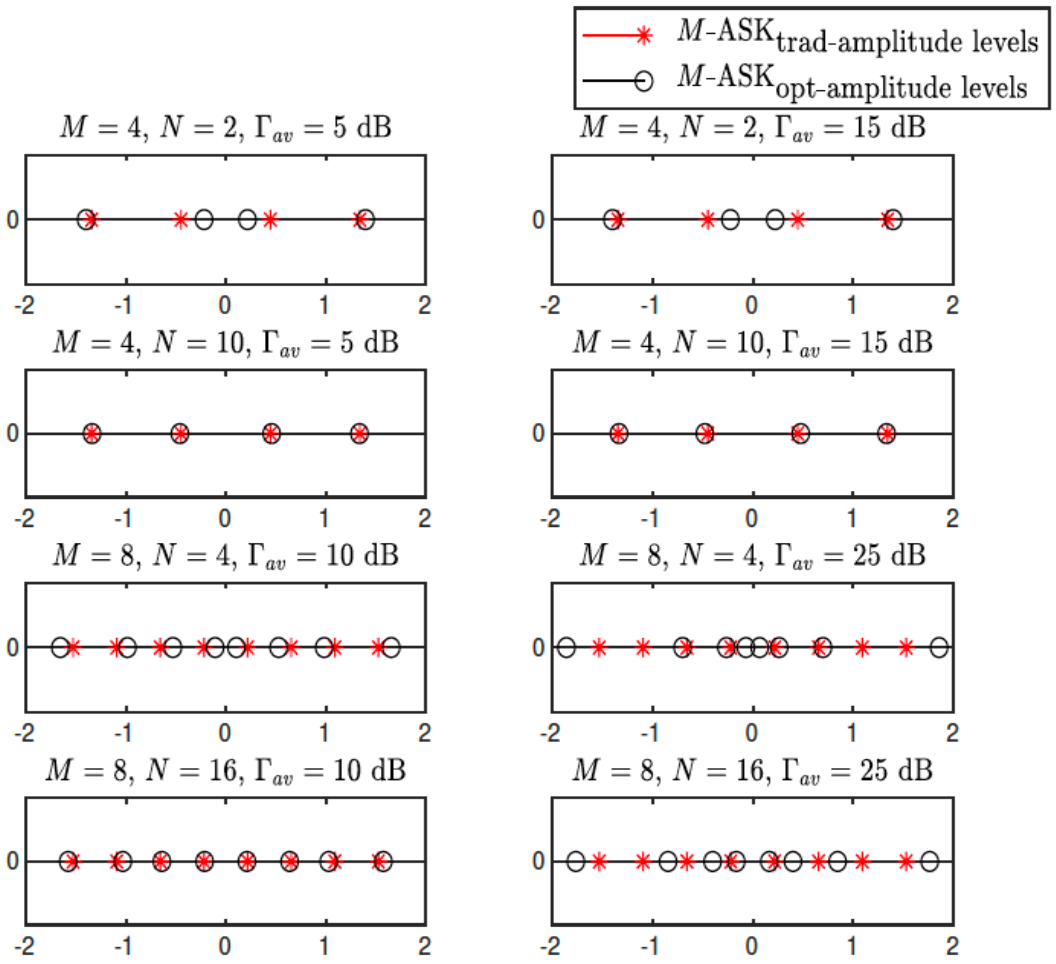


SEP versus average SNR using 4-level two-sided ASK



SEP versus average SNR using 8-level two-sided ASK

Numerical Analysis with Two-sided ASK



Traditional and optimal 4-level and 8-level two-sided ASK

- Similar to one-sided, the optimal two-sided performs better as compared to traditional two-sided ASK constellations
- Traditional two-sided ASK also faces SEP saturation and the use of optimal two-sided ASK improves the diversity of the system
- The optimal two-sided ASKs is not equispaced and the spacing between the constellation points depends on the system parameters
- Increasing number of diversity branches and increasing SNR reduces the constellation gaps between the two ASK schemes
- Such studies improves the reliability of practical, hardware-efficient noncoherent wireless communication systems

Conclusions and Future Work

- Noncoherent communications is a key technology to meet some essential KPIs of the next-generation wireless communication systems

- Noncoherent communications leads to the development of hardware- and energy-efficient receivers which has multiple applications is next-generation wireless communications' use cases

- Although noncoherent communications leads to a less reliable performance, a study is demonstrated to obtain optimal ASK constellations to address this issue

- The optimal ASK constellations are obtained to improve the error performance of a SIMO noncoherent system under Rician fading environment (modelling the channels for ultra-dense networks resulting in prominent LoS communications) under practical energy constraints at the transmitter

- Optimal one-sided and two-sided ASK constellations achieve a higher diversity order as compared to the traditional ASK schemes

- Such studies can be further applied to other system models such as RIS-assisted wireless systems

The work presented here have led to the following publications:

- B. R. Reddy, S. P. Dash, and D. Ghose, “Optimal multi-level amplitude-shift keying for non-coherent SIMO wireless system in Rician fading environment,” *IEEE Transactions on Vehicular Technology*, vol. 73, no. 3, pp. 4493-4498, March 2024.

- B. R. Reddy, S. P. Dash, and F. Y. Li, “Optimal M-level two-sided ASK for noncoherent SIMO wireless systems in a Rician fading environment,” *IEEE Communications Letters*, vol. 28, no. 6, pp. 1437-1441, June 2024.

THANK YOU