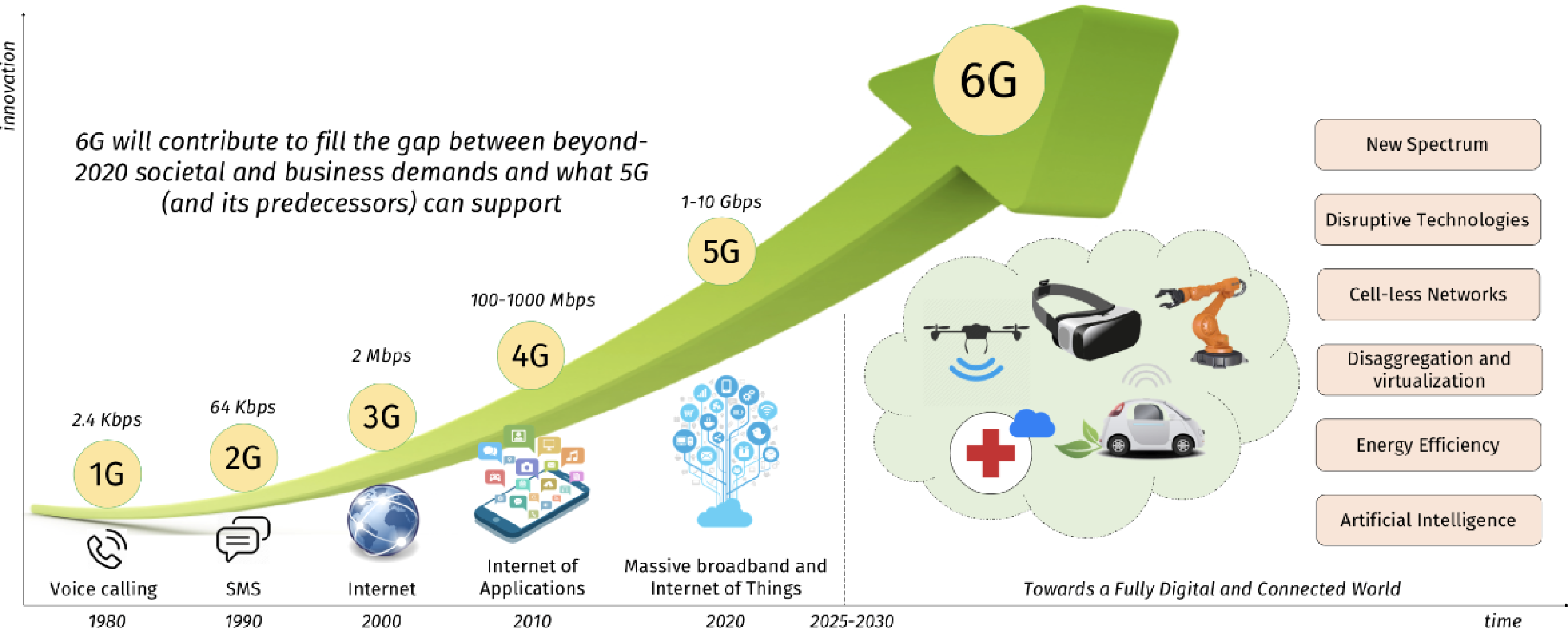
An Overview of AI for 6G Joint PhD Programs

Prof. Branka Vucetic
Centre for IoT and Telecommunications

THE UNIVERSITY OF SYDNEY

Evolution of Wireless Cellular Networks



5G Vision and KPIs

10,000 x more traffic

20Gbps DL peak data rates to support AR/VR

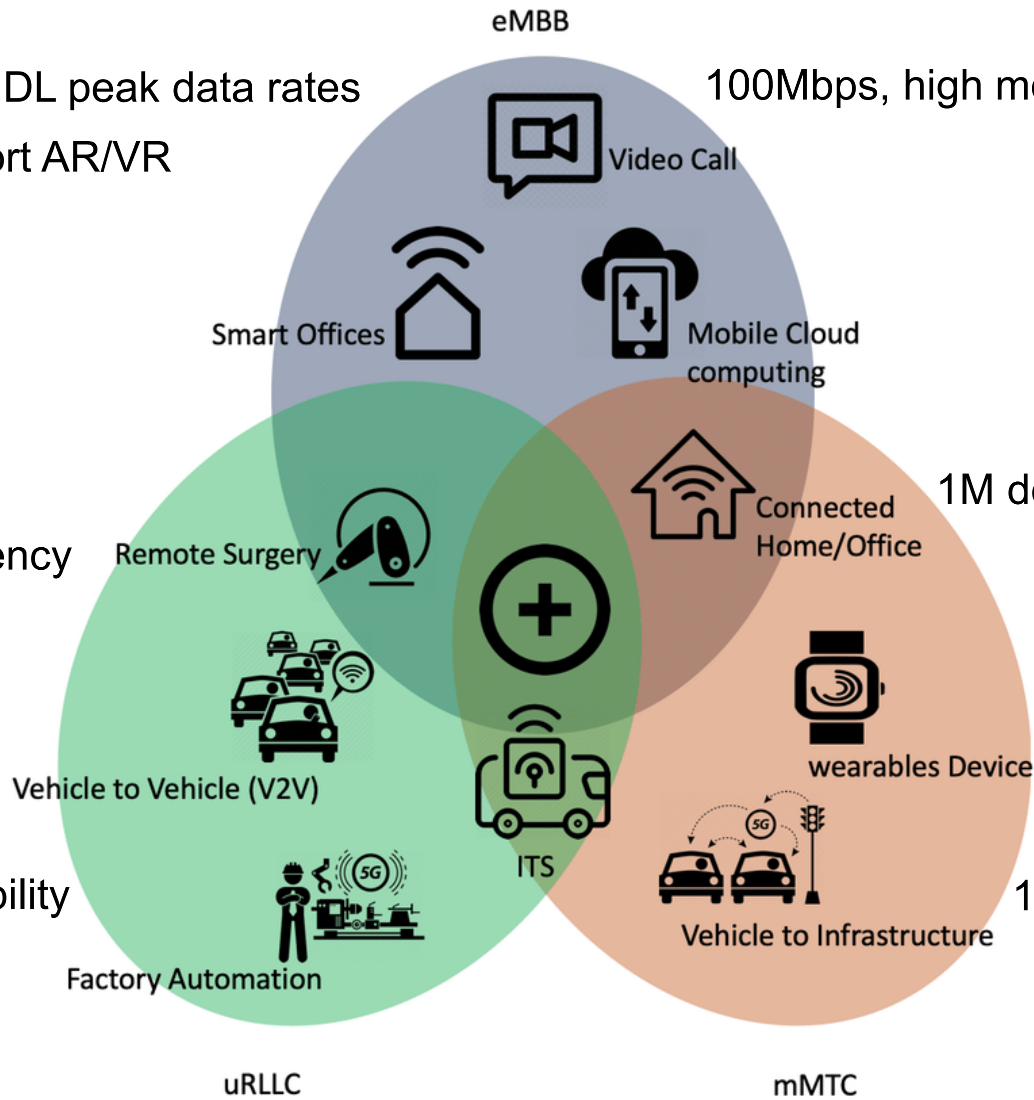
100Mbps, high mobility

1M devices per sqkm

1 ms latency

99.9999% reliability

10-year battery life



6G Vision and Possible Use Cases

Holographic connectivity

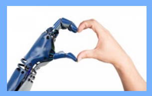
- Ultra-high fidelity VR/AR
- Holographic telepresence
- Multi-sense experience

Bio connectivity

- Wearable and implantable bio-sensors
- Healthcare applications
- Brain-machine communications
- Brain-brain communications

Ubiquitous connectivity

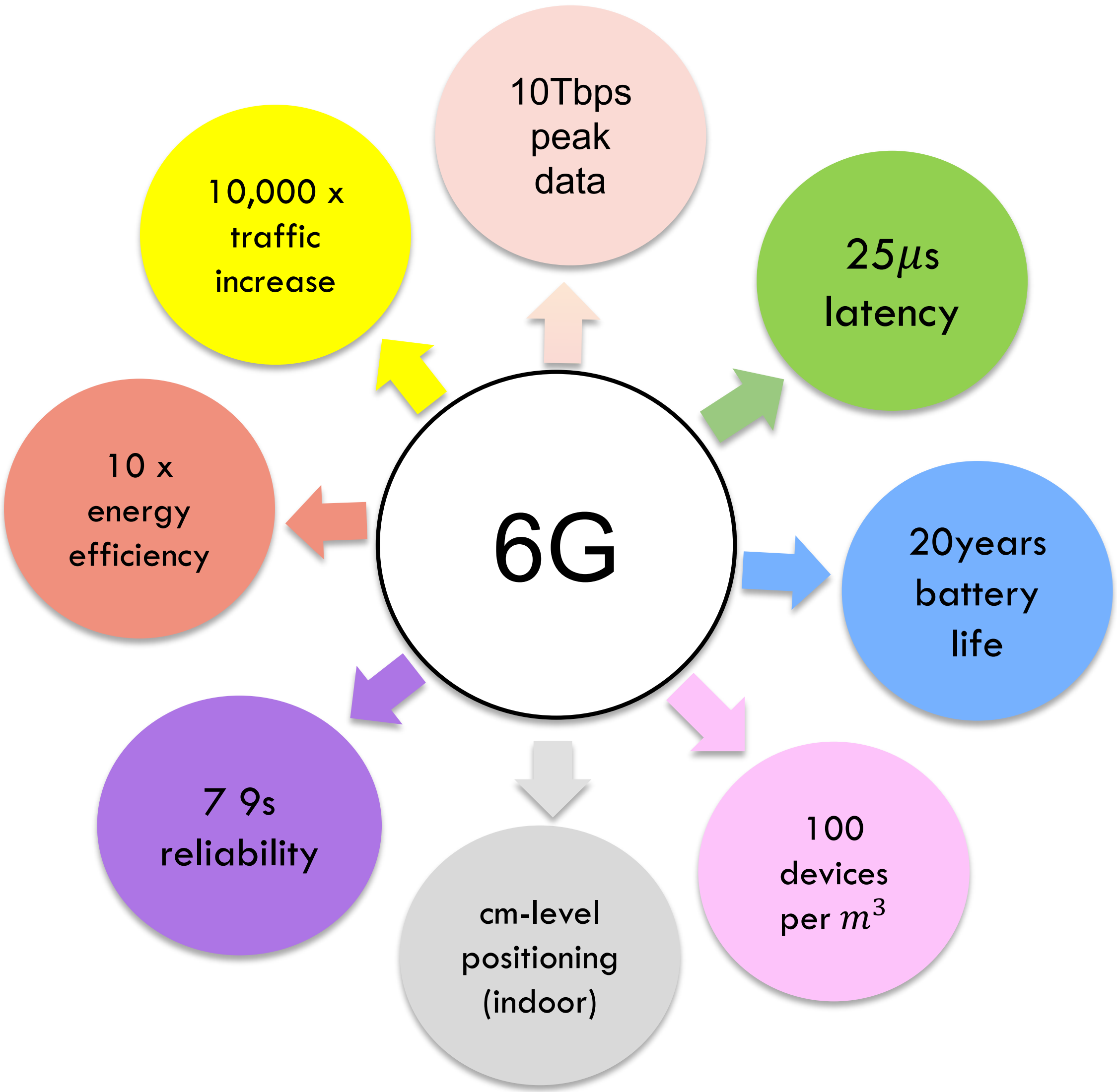
- Space
- Air
- Ground
- Underwater



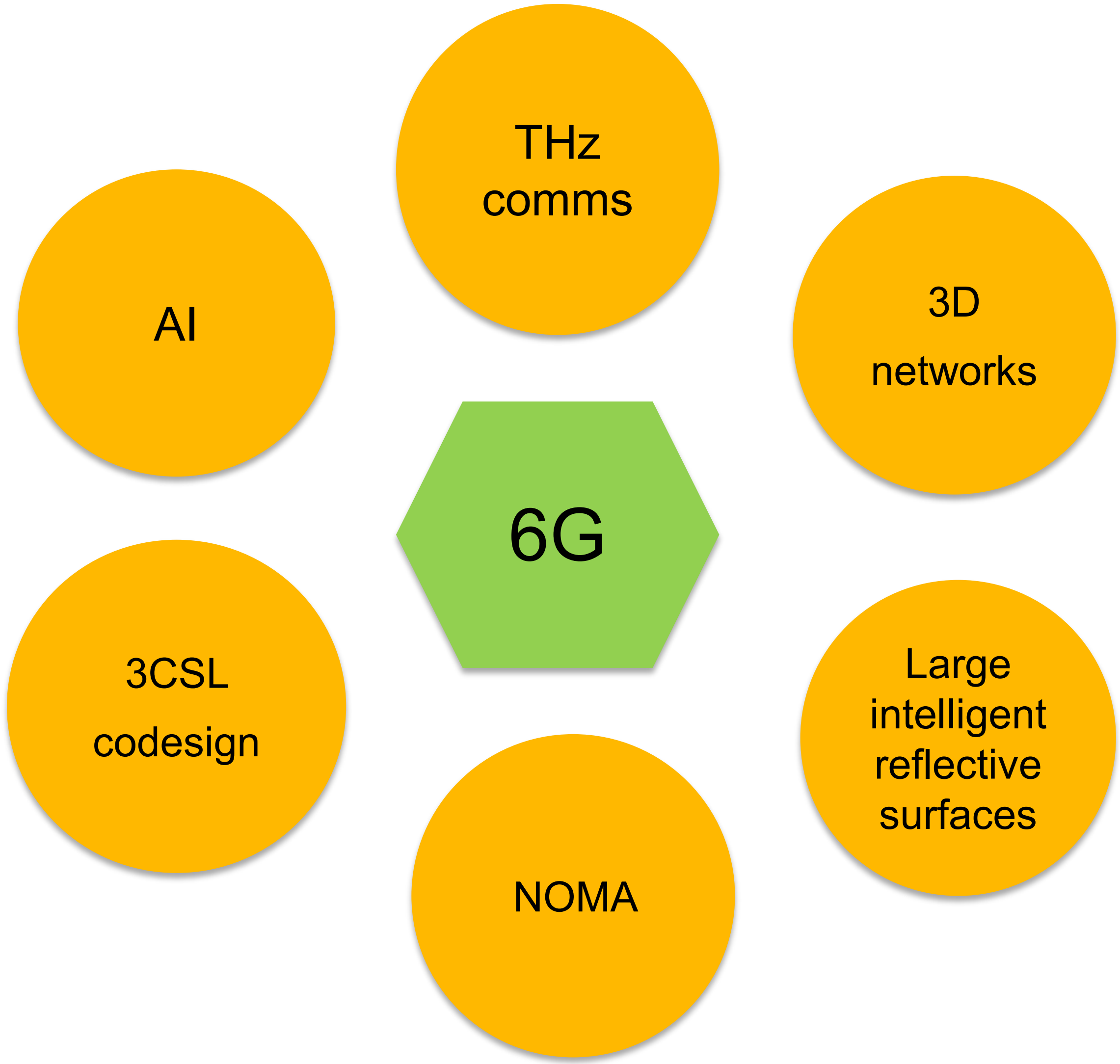
Deep connectivity

- Deep sensing and learning for IoT applications
- Human-machine collaboration
- Collaborative robots in factories and healthcare

6G KPIs

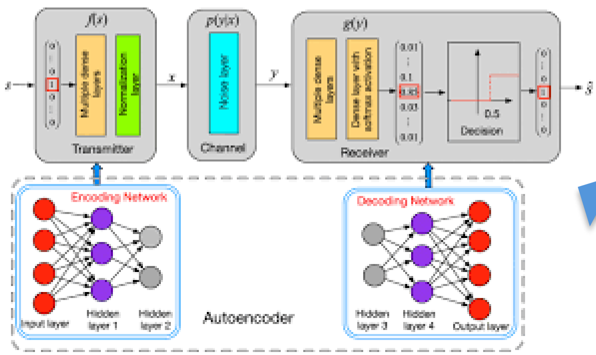

6G
10Tbps peak data
$25\mu s$ latency
20years battery life
100 devices per m^3
cm-level positioning (indoor)
7 9s reliability
10 x energy efficiency
10,000 x traffic increase

6GTechnologies



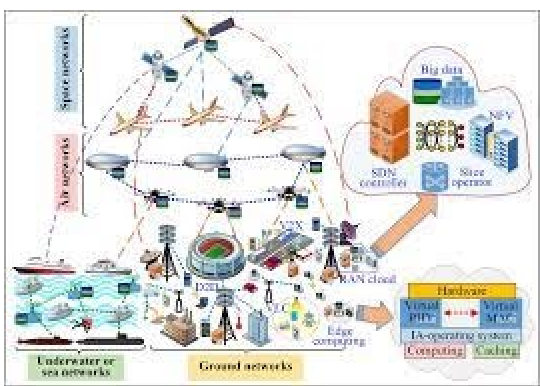
Use Cases for AI in Wireless Networks

5G/6G

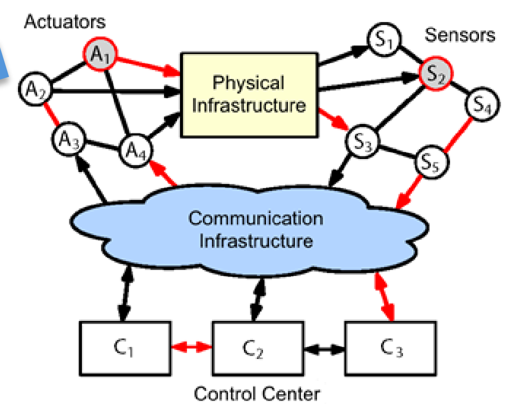


Physical layer design

Propagation and channel modelling



Network resource allocation



Communications and control co-design

Principles of Machine Learning in Wireless Networks

Data Collection

Data Cleaning

Model Building

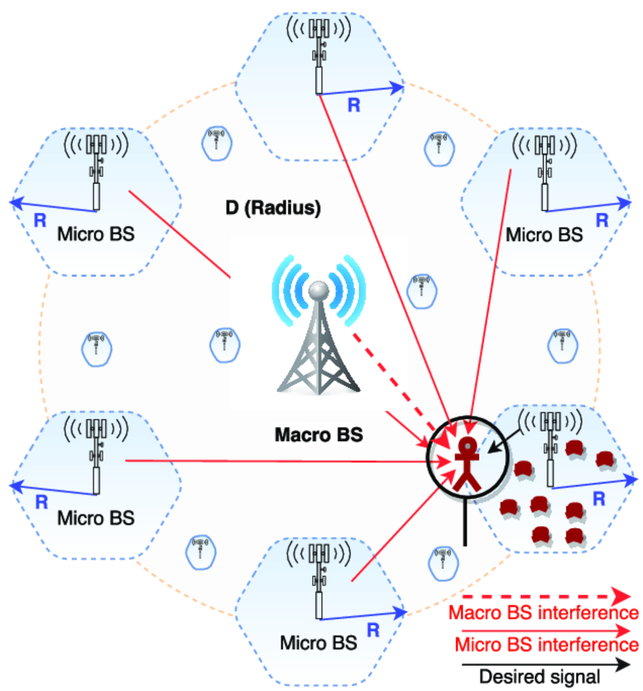
Training

Decision Making

Performance Evaluation

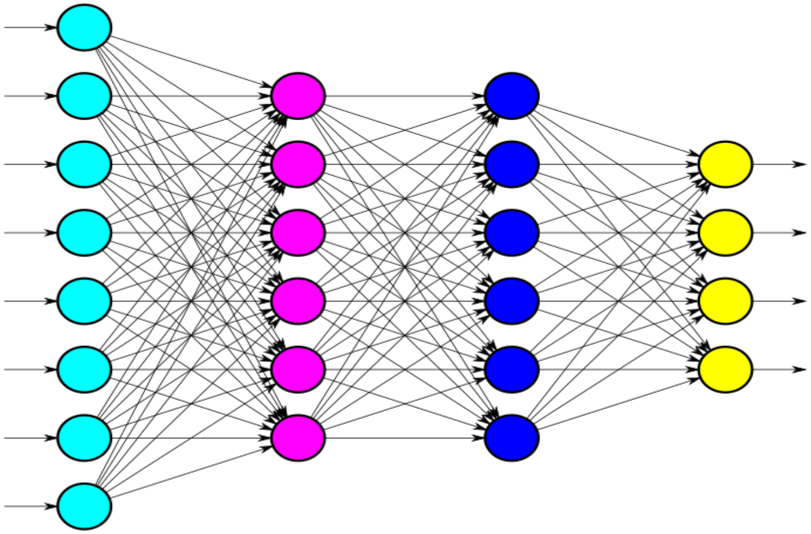
Signal Strength Prediction in Cellular Networks

- Signal strength information required for deploying communication towers
- Theoretical models are not accurate
- Real measurements give accurate signal strength values
- They are costly and inflexible
- AI-based models are superior for signal strength modelling

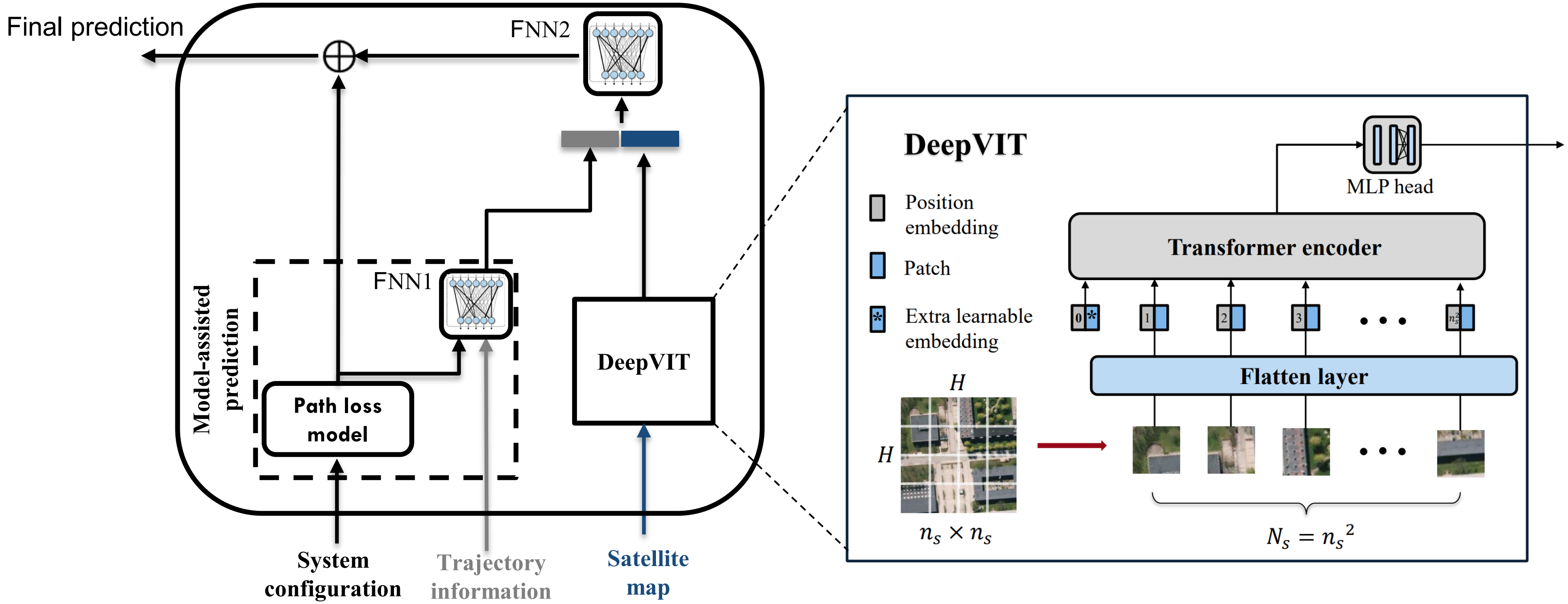


AI-based Signal Strength Prediction

- AI-based propagation modelling for outdoor environments
- The current empirical models use the information on transmit and receive antenna heights, frequency, and the distance between the transmitter and receiver, and correction factors for the environment types
- The AI model uses high-resolution satellite images that capture the environment features.



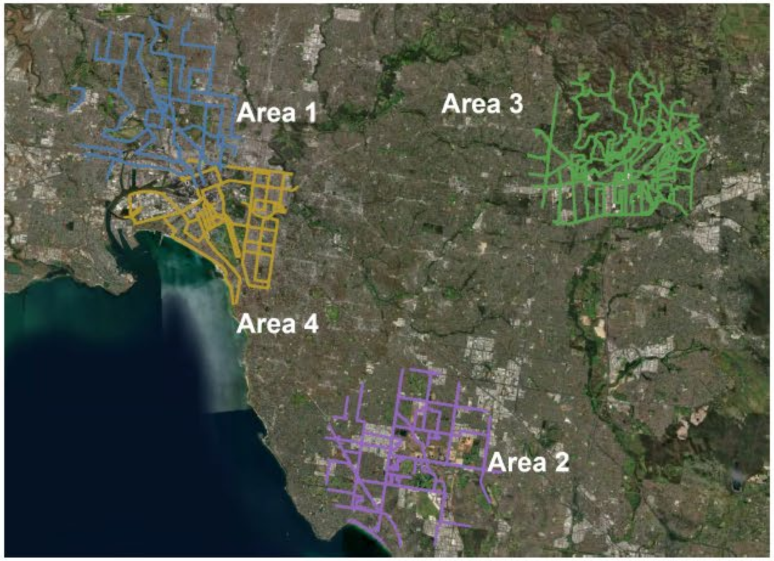
An AI Model for Propagation Modelling



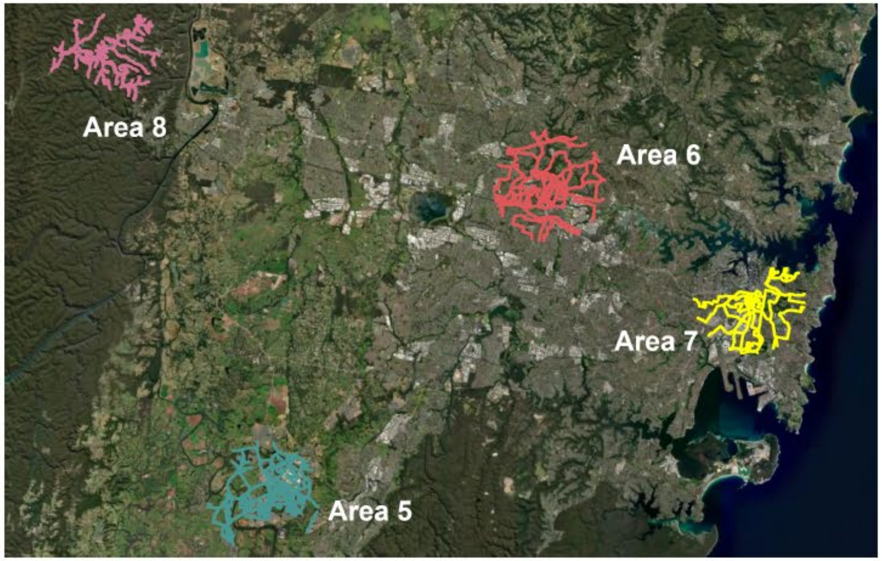
- System configuration: BS transmitter power, BS height, user height, and the ground distance between user and BS.
- Trajectory information: user location, BS location, and the ground distance.
- Satellite map: nearby satellite map of users

Yu, Z. Hou, Y. Gu, et al.," Systems and methods for received signal strength prediction using a d federated learning framework," A.U. Patent 051437, Dec. 2022.

AI-Based Propagation Modelling - LTE Telstra(2.6GHz)



(a) Sites from areas 1-4 in Victoria, Australia



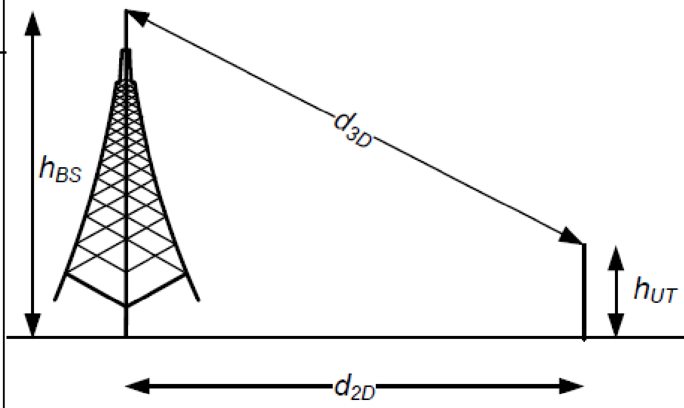
(b) Sites from areas 5-8 in New South Wales, A

The location of different sites

Prediction Results for LTE Signal Strength

– **Baseline : Path loss model (from 3GPP)**

UMa_A
LOS
$0.5\,\text{GHz} \le f_c \le 6\,\text{GHz}$ and $6\,\text{GHz} < f_c \le 100\,\text{GHz}$ $PL_{\text{UMa-LOS}} = \begin{cases} PL_1 & 10\text{m} \le d_{2\text{D}} \le d'_{\text{BP}} \\ PL_2 & d'_{\text{BP}} \le d_{2\text{D}} \le 5\text{km} \end{cases}$, see Note 3 $PL_1 = 28.0 + 22\log_{10}(d_{3\text{D}}) + 20\log_{10}(f_c)$, $\sigma_{SF} = 4$ dB $PL_2 = 40\log_{10}(d_{3D}) + 28.0 + 20\log_{10}(f_c) - 9\log_{10}((d'_{BP})^2 + (h_{BS} - h_{UT})^2)$, $\sigma_{SF} = 4$ dB



PL: Path loss

f_c: Carrier frequency

d_{2D}: Distance between base station and user in 2 dimension

d_{3D}: Distance between base station and user in 3 dimension

h_{BS}:Base station height

δ_{SF}:Shadow fading

h_{UT}: User height

d'_{BP}:Break point distance

3GPP TR 38.901 version 16.1.0 Release 16, "Study on channel model for frequencies from 0.5 to 100 GHz," Nov. 2020.

Prediction Results for LTE Signal Strength –Telstra

For each site: first 80% data for training and last 20% data for testing

Areas	AI-based model RMSE [dB]	Path loss model RMSE[dB]
Area1	**5.63**	**9.18**
Area2	**5.85**	**9.06**
Area3	**6.24**	**10.38**
Area4	**5.32**	**8.94**
Area5	**6.21**	**8.61**
Area6	**6.26**	**9.68**
Area7	**4.81**	**8.54**
Area8	**5.98**	**10.11**

H. Yu *et al*., "Distributed Signal Strength Prediction using Satellite Map empowered by Deep Vision Transformer," *2021 IEEE Globecom Workshops (GC Wkshps)*, 2021, pp. 1-6, doi: 10.1109/GCWkshps52748.2021.9682021.

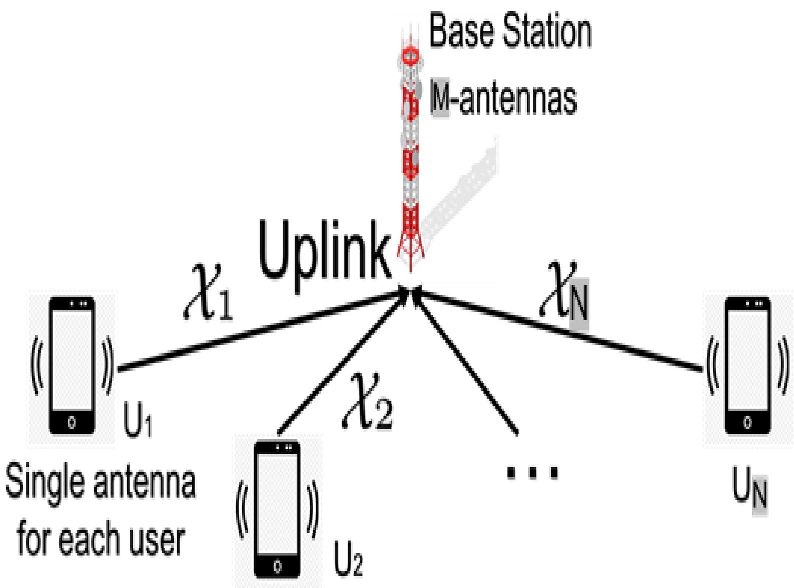
H. Yu, Z. Hou, Y. Gu, et al.," Systems and methods for received signal strength prediction using a distributed federated learning framework," A.U. Patent 051437, Dec. 2022.

Prediction Results for LTE Signal Strength –Telstra

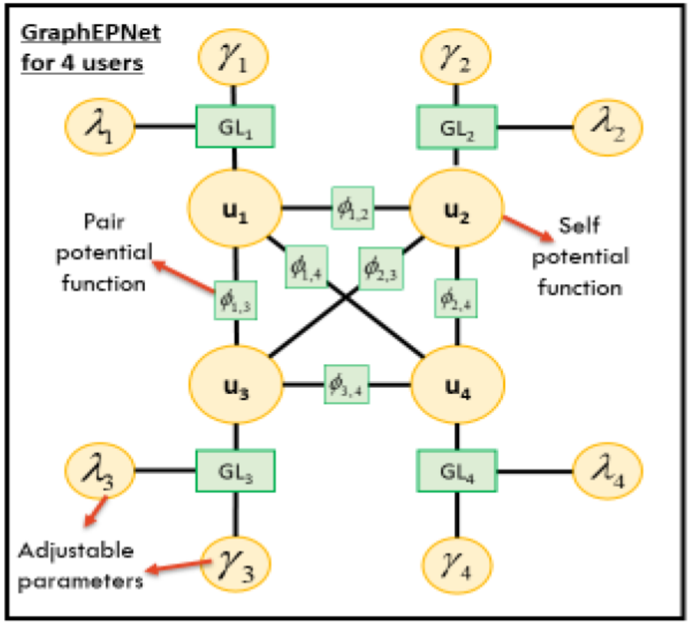
- **Training sites: Area1&2&3**
- **Testing sites: Area4**
- **Testing RMSE: 5.93dB**

- **Training sites: Area5&6&8**
- **Testing sites: Area7**
- **Testing RMSE: 6.33dB**

AI-based Detector Design in Massive MIMO Systems



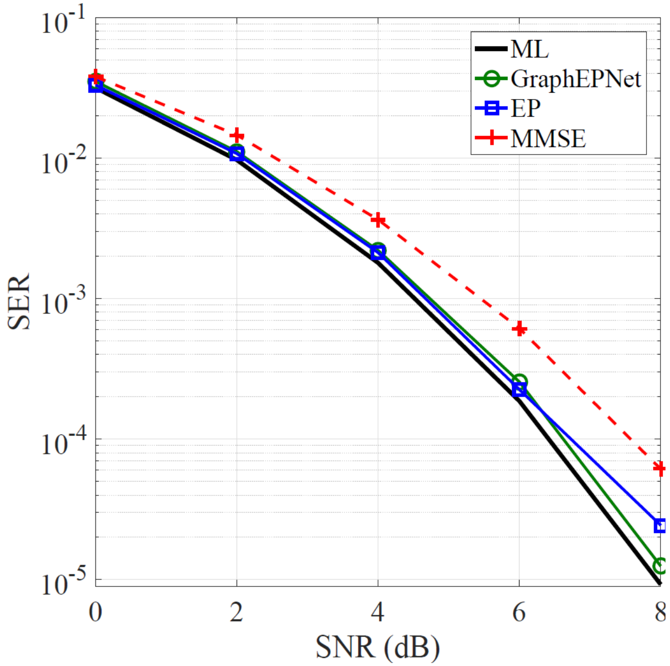
System Model



Graph Neural Network-based Detector

A. Kosasih, V. Onasis, V. Miloslavskaya, W. Hardjawana, V. Andrean, and B. Vucetic, Graph neural network aided MU-MIMO detectors, IEEE Journal on Selected Areas in Commun., Vol. 40, No. 9, July 2022, pp. 2540-2555.

Performance of the AI-based Detector in Massive MIMO Systems



Symbol Error Rate

System configurations:

- Quadrature Phase Shift Keying (QPSK)
- Number of Rx : 32, Tx : 8
- Total samples : 100000
- Batch size : 64
- Number of training iterations : 500
- Number of layers for each MLP : 3
- Hidden layer neurons in each MLP : 128
- Optimizer : Adam

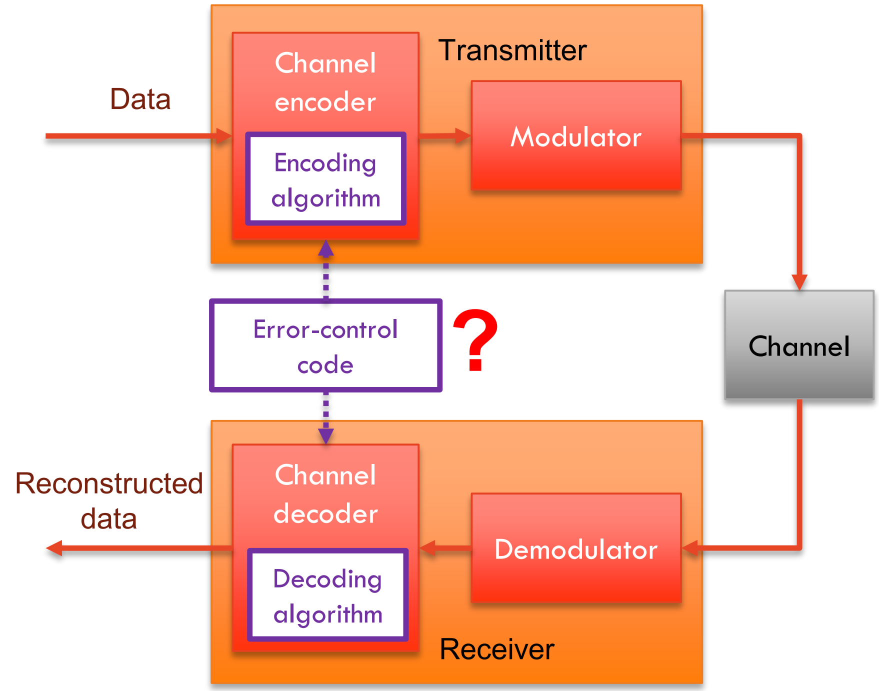
Receiver Complexity

Detector	Complexity	Complexity Values
Maximum likelihood	$O(A^N)$	4294967296
Minimum mean square error	$O(M^3)$	430080
Expectation propagation	$O\left((M^3 + M^2N + MN^2)T\right)$	124288
GraphEPNet	$O\left((N^2 + MN + L)T\right)$	32768 (26% of EP)

N – the number of users, each with a single antenna
M – the number of base station antennas
A – the number of points in the constellation set
T – the number of iterations
L – the number of neurons

AI-based Error-Control Code Design for 6G

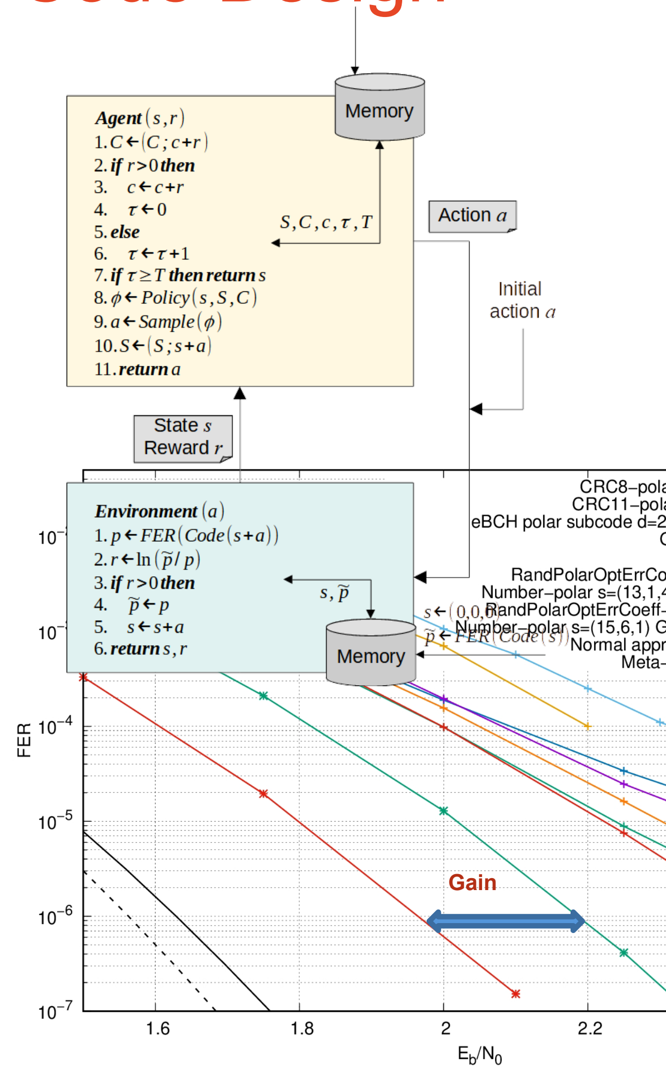
- Beyond 5G and 6G networks:
  - Channel codes with high error-correction capability are needed to meet the stringent reliability, latency and throughput requirements of emerging applications
- Start-of-the-art codes:
  - 5G New Radio standard:
    - **Polar codes** with cyclic redundancy check (CRC) were adopted for control channel
    - Low density parity check (LDPC) codes were adopted for data channel
- Can AI improve the complexity-performance tradeoff?



.

Reinforcement Learning-based Polar Code Design

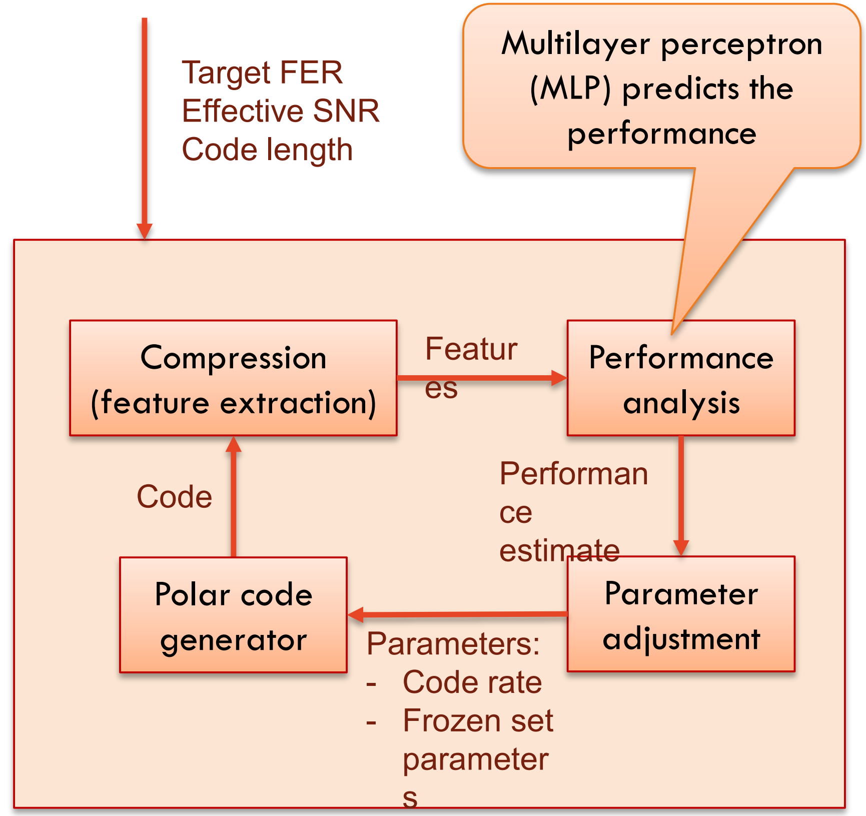
- Flexible construction
  - Code optimization using **reinforcement learning** for the SCL decoder with any list size
  - Agent's actions are sampled in accordance with the policy
  - The proposed policy benefits from our frame error rate (FER) prediction approach
  - Applicable for various code lengths and rates
- Low description complexity
  - Each code is specified by just three integer parameters, while the reliability sequence is fixed
- High error-correction capability under SCL decoding
  - Provide lower FER than the state-of-the-art polar code constructions (5G polar codes with CRC11, randomized polar subcodes, and polar codes optimized using artificial intelligence techniques).
  - Codes of lengths 512, 1024, 2048 and 4096 are considered
  - (512,256) code is within 0.2 dB from the normal approximation bound
- The proposed codes are potential candidates for beyond 5G and 6G networks

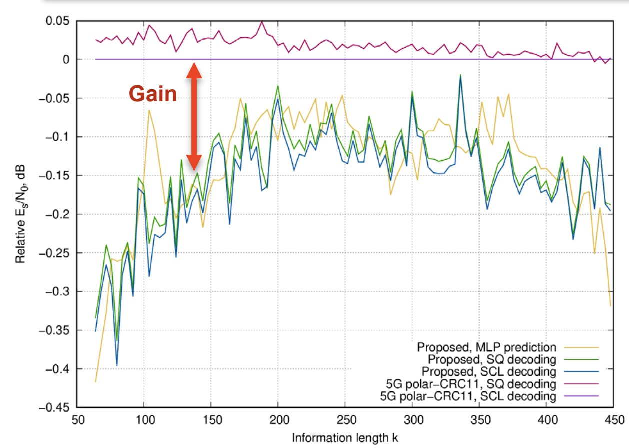


(1024,512) codes under SCL decoding

AI-based Adaptive Polar Coding for Time-Varying Channels

- Transmitter performs adaptive coding based on the actual channel state information
- Precoded polar code is adjusted for given target FER, effective SNR and code length
- The key elements are the code feature extractor and FER predictor
  - Six features are extracted
  - The features are fed to the multilayer perceptron (MLP), which returns a performance estimate. The MLP is trained based on simulation results for a few codes. A single MLP is used for various target FERs, decoding list sizes L and code parameters.
- Bit-level optimization of the number of information bits
- The proposed approach is suitable for precoded polar codes with various structures
- Description complexity
  - 5G polar codes: a reliability sequence consisting of 1024 integers
  - Overhead of the proposed approach compared to 5G: 65 weights defining the MLP





The relative Es/N0 for the target FER 10^{-3}, where the 5G polar codes with CRC11 under SCL decoding are used as zero level

Code length n=512
Message length k=128,…,384
Decoding with list sizes L=8
Successive cancellation list (SCL) decoder
Sequential (SQ) decoder

V. Miloslavskaya, Y. Li, and B. Vucetic, "AI-Based Adaptive Polar Coding", Submitted to IEEE Transactions on Communications in March 2023.

AI-based Error-Control Code Design for 6G

Blocklengths 32 and 64: V. Miloslavskaya and B. Vucetic, “Design of short polar codes for SCL decoding,” *IEEE Transactions on Communications*, vol. 68, no. 11, pp. 6657–6668, November 2020.

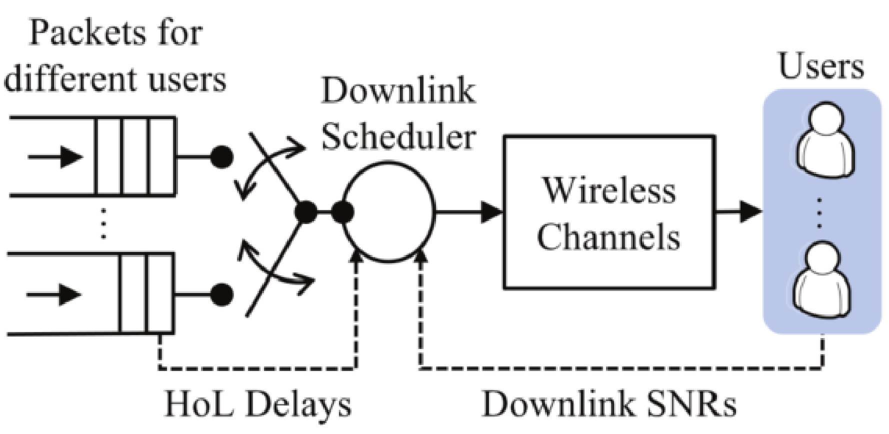
Blocklengths 128 and 256: V. Miloslavskaya, B. Vucetic, Y. Li, G. Park, and O.-S. Park, “Recursive Design of Precoded Polar Codes for SCL Decoding”, *IEEE Transactions on Communications*, vol. 69, no. 12, pp. 7945–7959, 2021.

Blocklengths 512 to 4096: V. Miloslavskaya, Y. Li and B. Vucetic, “Design of Compactly Specified Polar Codes with Dynamic Frozen Bits Based on Reinforcement Learning”, *submitted to IEEE Transactions on Communications*.

Analysis of precoded polar codes: V. Miloslavskaya, B. Vucetic and Y. Li, “Computing the Partial Weight Distribution of Punctured, Shortened, Precoded Polar Codes”, *submitted to IEEE Transactions on Communications*.

AI-based Scheduler Design

- Scheduling is allocation of communication resources
- Its input is the queue state of the packets in a buffer and channel state information
- The output is the amount of communication resources allocated to each user
- This is a sequential decision-making problem
- Analytical resource allocation is too complex



Deep Deterministic Policy Gradient-Based Scheduling Design

- The scheduling optimisation problem can be solved by Deep Deterministic Policy Gradient (DDPG) algorithm

$\mathbf{s}(t)$
- HoL Delays
- Downlink SNRs

$\mathbf{a}(t)$
- Users to be scheduled
- Number of resource blocks

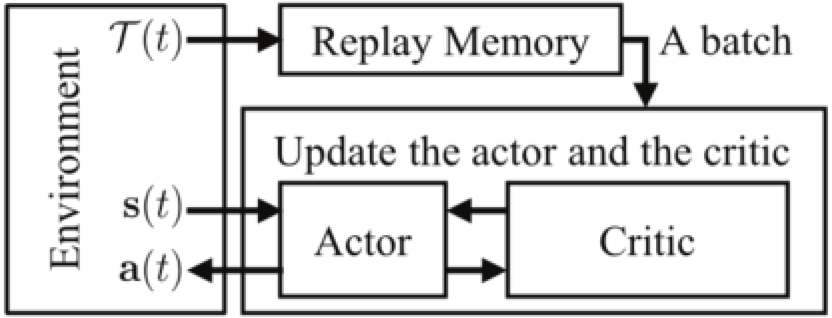


Fig. 2: Illustration of DDPG.

DDPG Combined with Expert Knowledge

- Straightforward implementation of DDPG converges slowly
- Models, theoretical formulas, and expert knowledge can reduce the convergence time
- By using expert knowledge on the topology of the wireless networks, the potential reward of visiting a state, and the importance of different samples, the scheduling decision is updated according to real-world feedback every few milliseconds, and the inference is executed within each TTI in 5G NR

AI-based Wireless Scheduler Design

5G Time-Sensitive Networks:

- Low Latency
- High Reliability
- Jitter

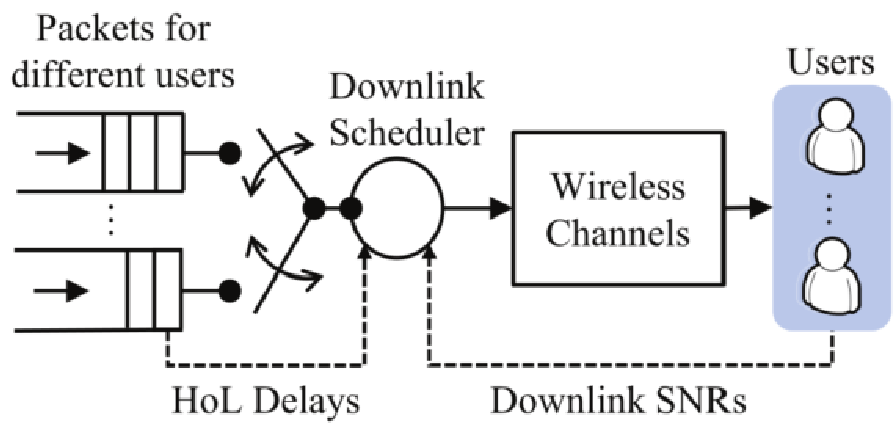
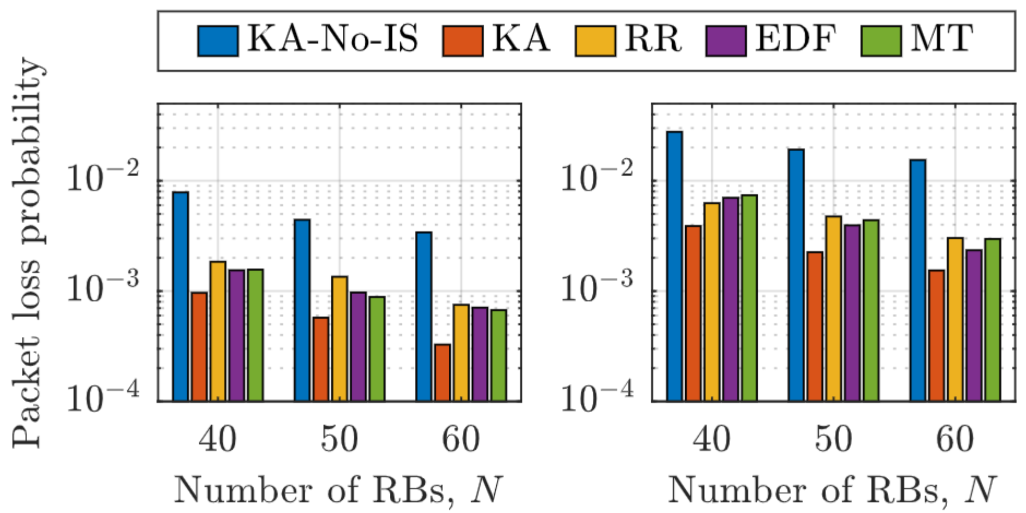


Fig. 1: Illustration of downlink scheduler.

Solutions:

- Domain knowledge-assisted DRL
- Straightforward implementation
- Traditional scheduler



(a) (b)

AI-based Joint Communication-Control Codesign

– **Jointly optimizing the scheduling, remote estimation, and control algorithm is a high-dimensional problem**
– **The AI based method is powerful in this kind of problem**

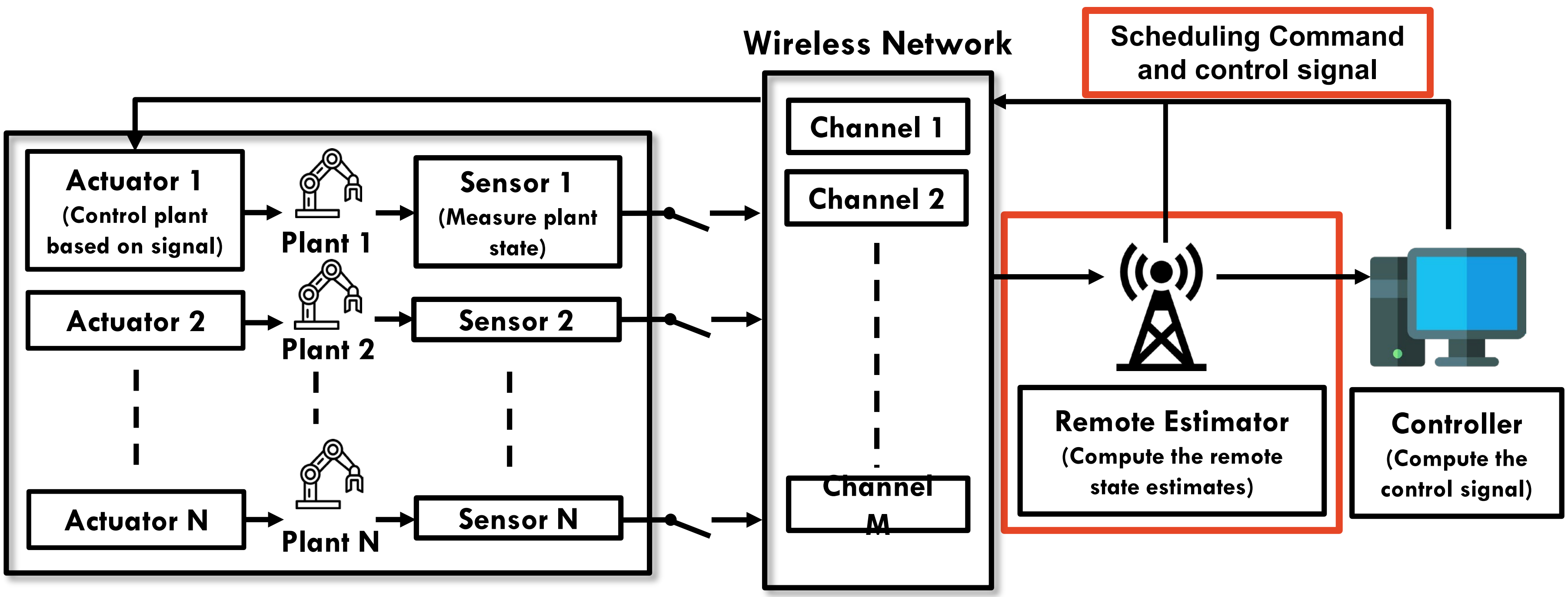


Fig. 1: An illustration of Wireless Networked Control System (WNCS)

AI-based Codesign Framework

– **Joint training of AI-based controller, estimator, and transmission scheduler**

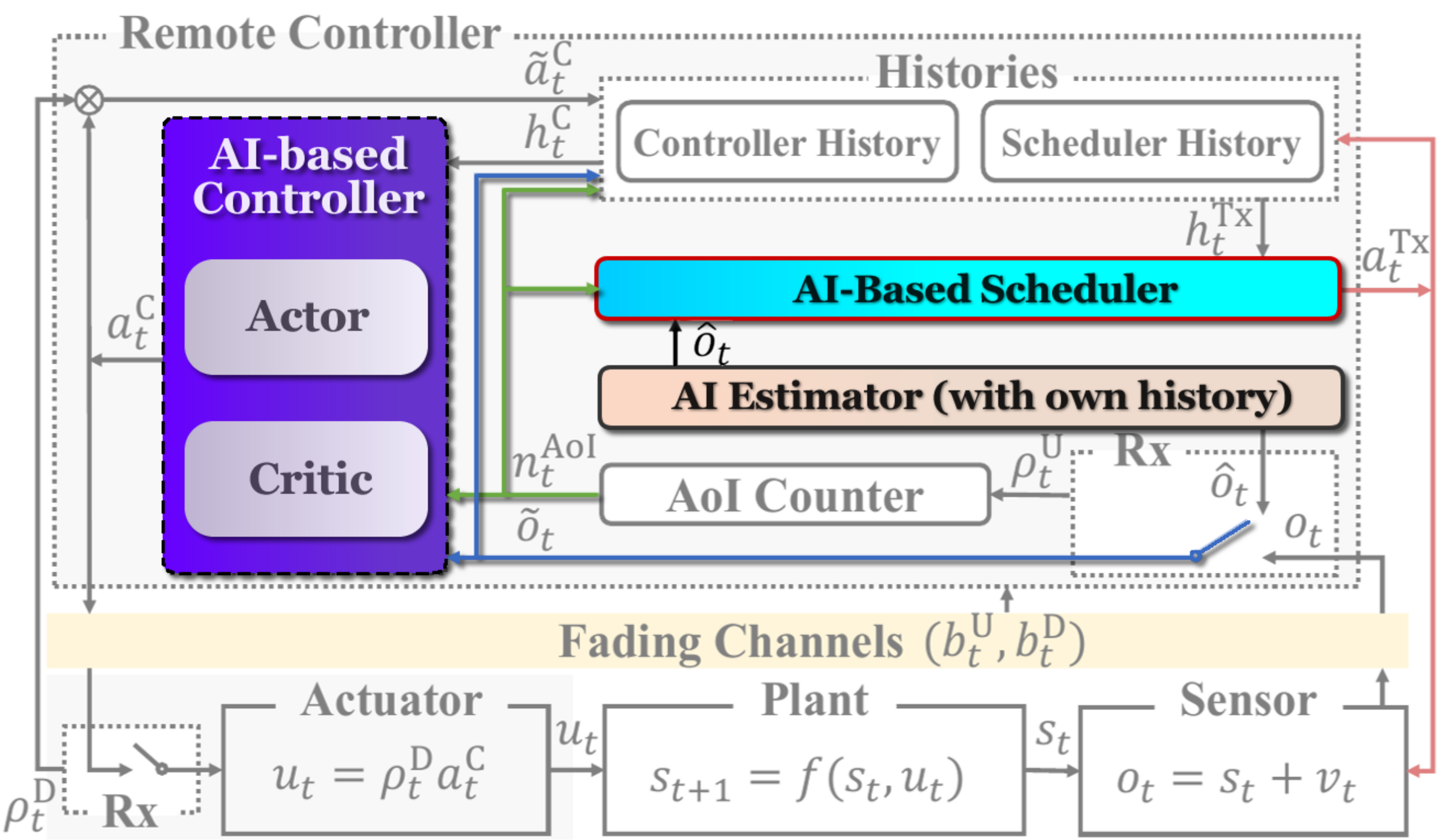


Fig. 2: Joint estimation-control-scheduling design in WNCS

Performance of Codesign

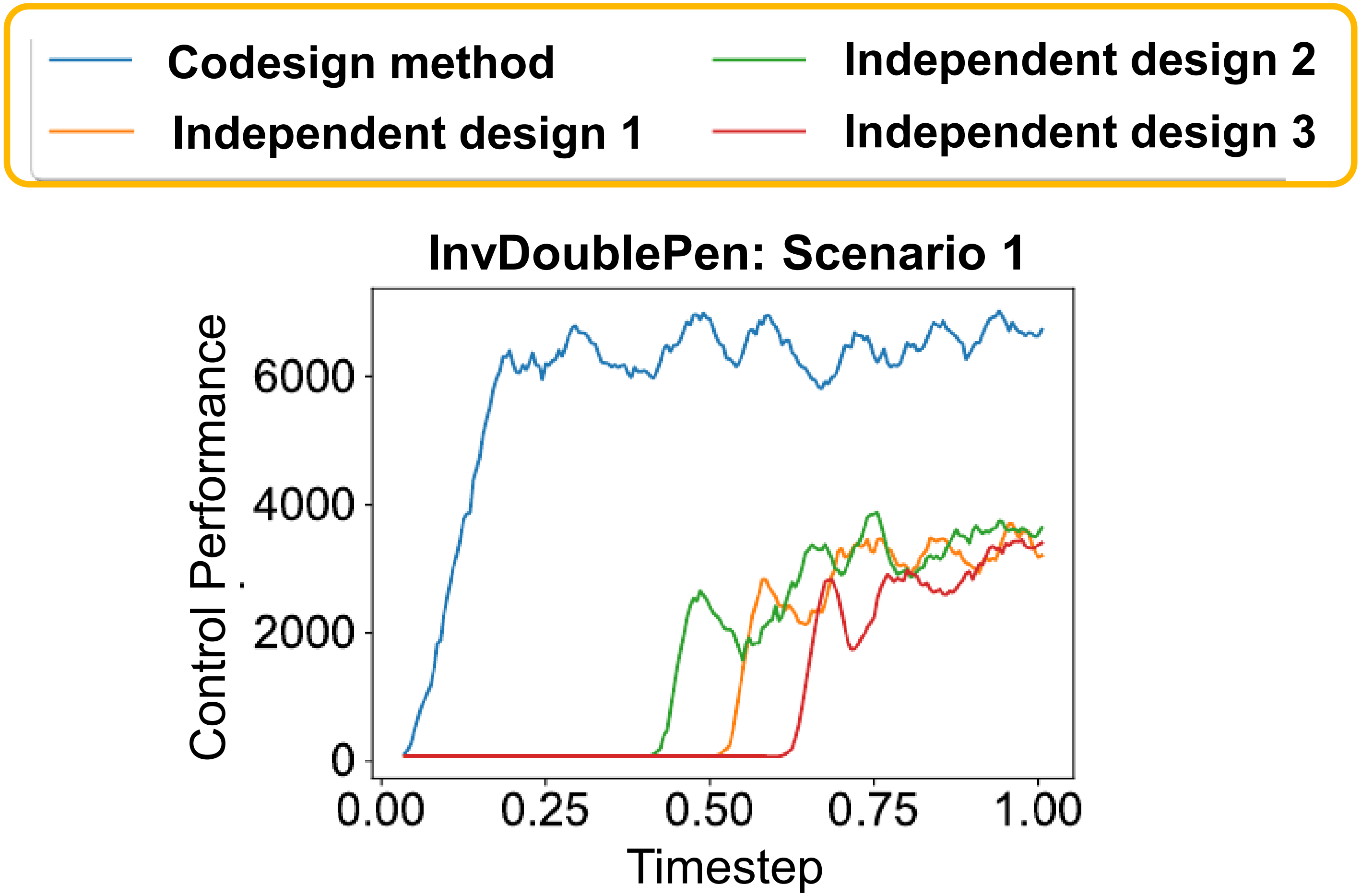


Fig. 4: Comparison of learning curves (low-mobility scenarios)
– joint and separative estimation-control methods

- Z. Zhao, W. Liu, D. E. Quevedo, Y. Li, and B. Vucetic, “Deep learning for wireless networked systems: a joint estimation-control-scheduling approach,” arXiv preprint, Oct. 2022. [Online]. Available: https://doi.org/10.48550/arXiv.2210.006

Conclusions

- AI is a useful tool for communications system and network design
- It enables more accurate propagation modelling where environment features could be obtained from images
- AI can reduce the complexity of physical layer algorithms and resource allocation protocols
- It can improve the performance of networked control systems by joint design
- 6G will be an intelligent platform with integrated communications, sensing, control, computing, and localization and it will enable distributed AI

Joint PhD model

THE UNIVERSITY OF
SYDNEY

Joint PhD Programs

Definition	Important Elements
A joint PhD is a Doctor of Philosophy program that consists of: • shared candidature between USYD and one or more institutions; • produces a single thesis; • jointly awarded by USYD and the partner institution.	• Enrolment at each institution; • Must meet admission requirements at both institutions; • Co-supervision by academic(s) from USYD and partner institution(s); • 2 separate testamurs that each acknowledge the joint arrangement; • Typically, coursework is only required at home institution; • Principal Agreement vs Student Agreement • Minimum of 30% of the candidature is spent at each institution.

Joint PhDs: Motivations and Benefits

Institutional Benefits	Student Benefits
• Institutional prestige • Complements existing research collaborations • Access to high quality international students	• Expansion of professional network / opportunities • Cross-cultural learning and experiences • Access to labs or source materials that may not be available at the home institution • No fees at the host institution!

Partners

Current partnerships:

Partner Institution	Country	Collaboration Tier
University of Glasgow	Scotland	Multi-faculty
University of Copenhagen	Denmark	Multi-faculty
Sorbonne University	France	Multi-faculty
Aix-Marseille University	France	Multi-faculty
Ca ‘Foscari University of Venice	Italy	Faculty-level
Grenoble Alpes University	France	Faculty-level

Partnerships under negotiation (AUFRANDE Program):

Partner Institution	Country	Collaboration Tier
University of Bordeaux	France	Faculty-level
École Centrale de Lyon	France	Faculty-level
University Paris-Est Créteil	France	Faculty-level
Arts et Métiers ParisTech	France	Faculty-level

Financial Model

Breakdown	Remarks
Tuition fees	Fee-waiver/exchange model (Tuition is paid at the home institution and waived at the host institution)
Living stipends	Students can apply for a broad range of scholarships
Travel & accommodation	May be partially covered by scholarship by home and/or host institution (e.g. $5,000 SGM Joint PhD Travel Scholarship)

CIoTT Team – Academic and Professional Staff

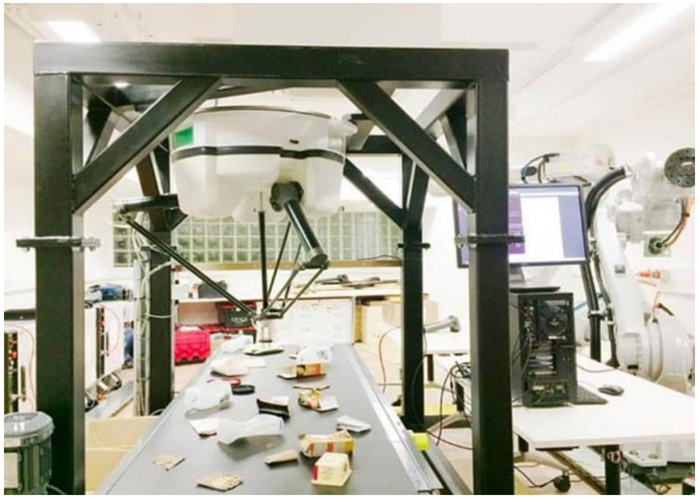
- 9 academic staff (5 profs, 1 assoc prof and 3 senior lecturers)
- 11 research associates (2 DECRAs)
- 1 technical officer
- 1 research administrator
- 1 adjunct professor
- 1 adjunct lecturer
- 47 HDR students (38PhD and 9MPhil)
- UG&PG capstone project students 125

Research Focus

- 5G and 6G wireless systems and networks
- Advanced satellite communication systems
- Wireless and IoT and security
- IoT applications in smart grids, healthcare, and material recovery facilities
- Long-range WiFi

CIoTT Strengths

- High national and international subject ranking (46th in 2018, 21st in 2021 and 9th in 2022 by ARWU)
- Advanced laboratory equipment (SDN, RF, networked control and industrial robots)
- Critical mass in communications, networking, PHY and IoT security (5 IEEE Fellows)
- Multiple government and industry research grants
- Service in IEEE societies and journals



Proof of Concept Demonstrators

- Recycling robot, IQRenew
- Long-range WiFi for mining, Roobuck
- Low-latency WiFi and AGV for warehouse automation, Damon, ABB
- 4G/5G open source SDR/SDN testbed, collaboration CFEN, and Nokia
- MAC schedulers and rate control in IEEE 802.11ah, Morse Micro
- AI based 5G propagation modelling, Optus
- Heart monitoring and AI-based diagnostics, Westmead Applied Research Centre and St Vincent Hospital
- Brain-machine communications
- Collaborative robot

Performance of Codesign

– Experient setups

HalfCheetah-v2

Hoper-v2

InvertedDouble Pendulum-v2

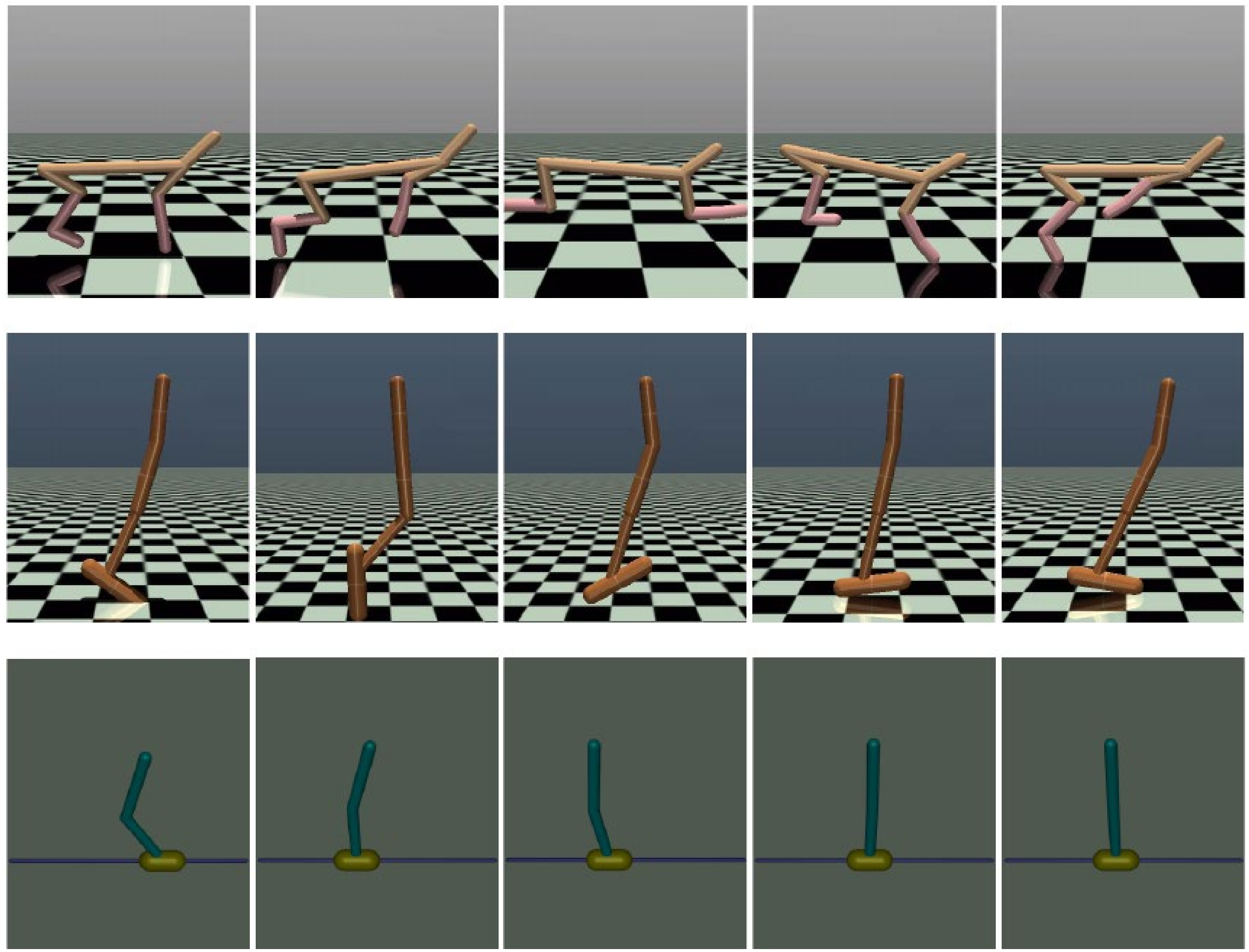
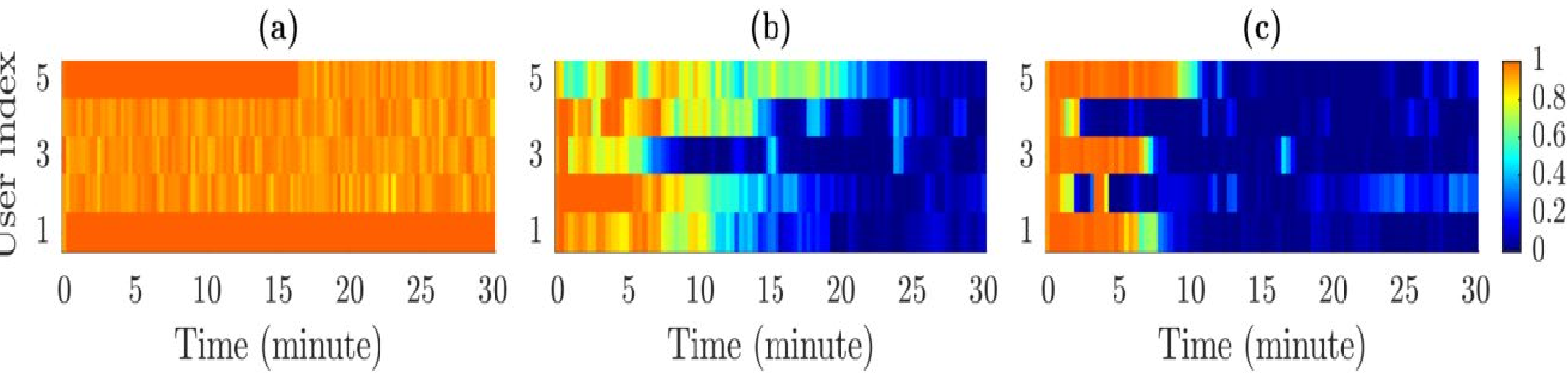


Fig. 3: Control objectives of MuJoCo tasks

Packet Loss Probability Results

- (a) Straightforward implementation of DDPG
- (b) DDPG with theoretical formulations in information theory
- (c) DDPG with expert knowledge on scheduler design problem



- The color represents the packet loss probability (orange is high, blue is low)
- The results indicate that theoretical formulations and expert knowledge can help improve the convergence time and final reliability remarkably.