UK-China Science Bridges:
R&D on 4G Wireless Mobile Communications

Research on Wireless Communications at Heriot-Watt University

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Outline

I. Research Environment

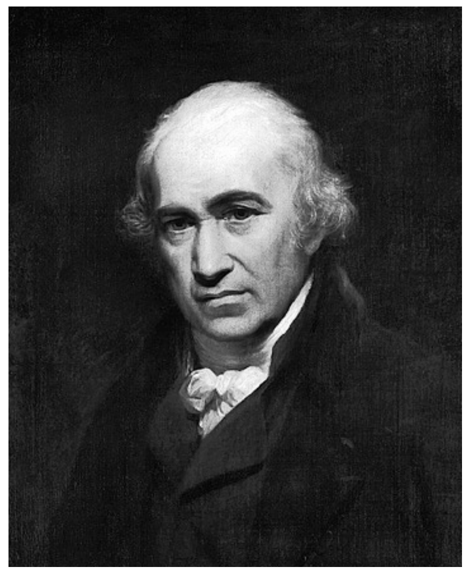
II. Research Areas and Projects

III. Suggested Collaboration Topics for Collaborations

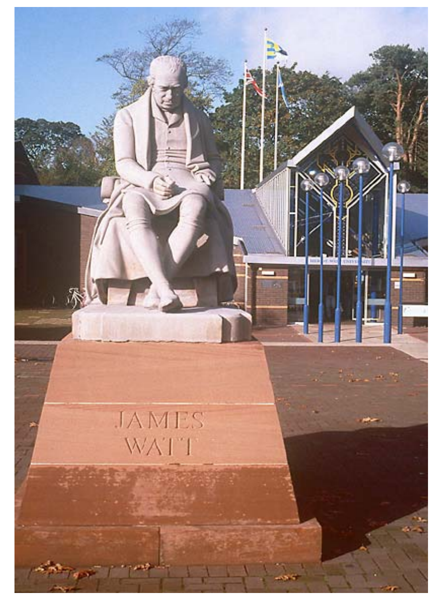
I. Research Environment

- Heriot-Watt University (赫瑞·瓦特大学):
  - Eighth oldest higher education institution in the UK;
  - Founded in 1821; Awarded University status by Royal Charter in 1966;
  - The name: commemorating two champions (George Heriot & James Watt) of commerce, education and technology;
  - 4 campuses: Edinburgh (main campus), Scottish Border, Dubai, Okney
  - RAE 2008: General Engineering (Electrical, Mechanical, Petroleum) ranked 6th in the UK

George Heriot, financier to King James VI and benefactor of education in Edinburgh (1563 - 1623)

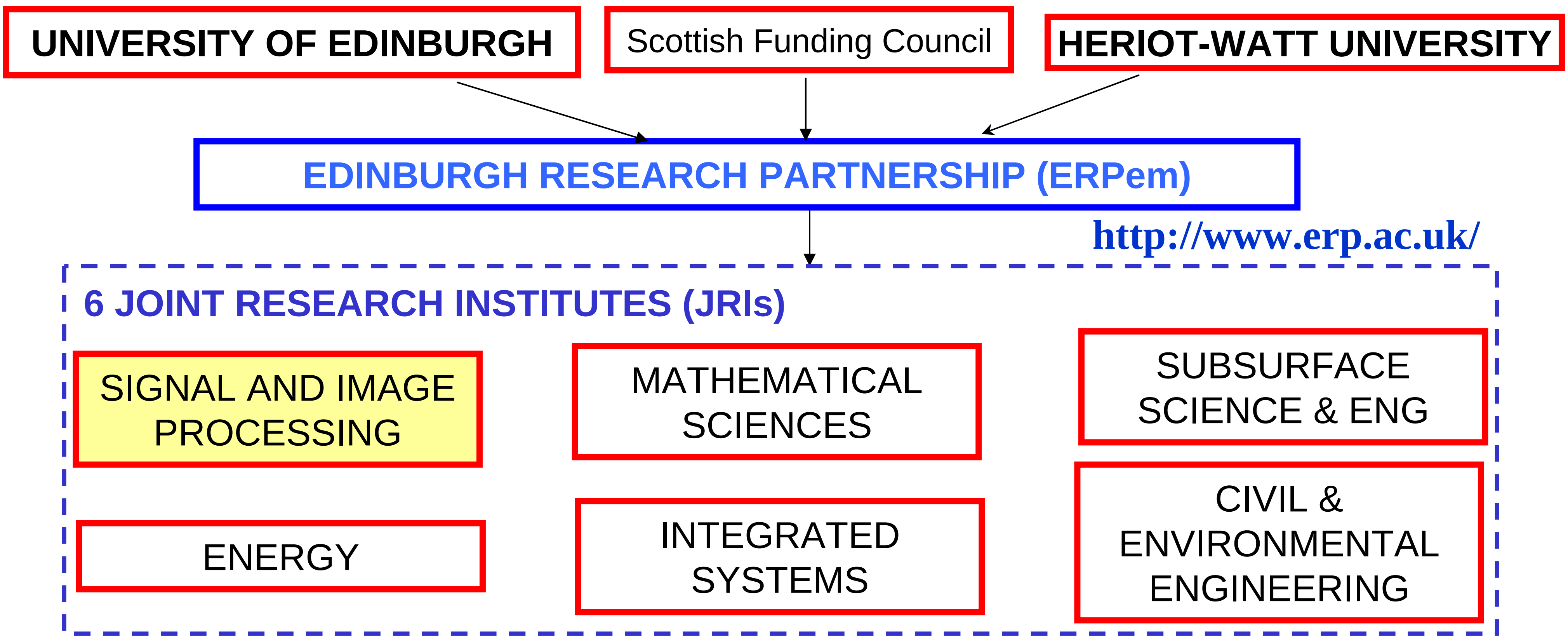


James Watt, the great 18th-Century Scottish engineer and pioneer of steam power



Edinburgh Research Partnership in Engineering and Mathematics (ERPem)

- **Heriot-Watt University** and the **University of Edinburgh**: collaborative research venture in Engineering and Mathematics, creating a critical mass of world-leading researchers.
- 2005-2010 (5 years); £22m investment; 26 new academic positions



RESEARCH COUNCILS UK

ERPem Edinburgh Research Partnership in Engineering and Mathematics

HERIOT WATT UNIVERSITY

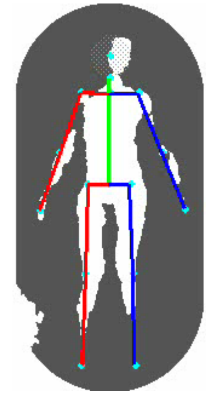
Joint Research Institute for Signal & Image Processing (JRI-SIP)

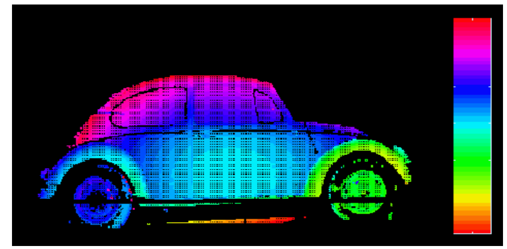
- Academic staff: 22
  - 10 academics, Institute for Digital Communications (IDCOM), UoE
  - 12 academics, Signal and Image Processing Group, HWU.
- Scale of activity: 2008-09
  - **Publications**: Journal 63, Conference 104
  - **New Research Awards**: ~£6.4m
  - **Industrial Research ad consultancy:** £0.75m
  - **Post Doctoral Researchers**: 27
  - **PhD Students**: 79
  - **Postgraduate Taught MSc Students:** 99

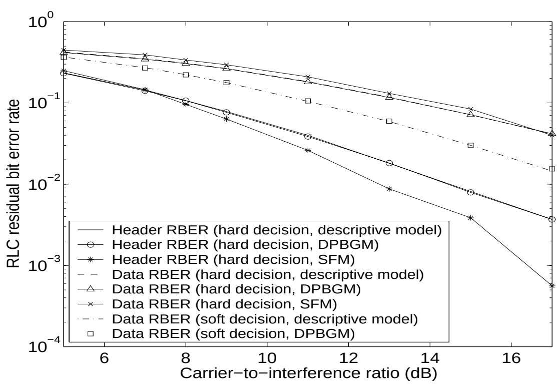
HWU (12):	**UoE (10):**
Dr Alexander Belyaev	**Dr Pei-Jung Chung**
Dr Keith Brown	**Prof Mike Davies**
Dr Mike Chantler	**Prof Peter Grant**
Dr Daniel Clark	**Dr Harald Haas**
Dr Paolo Favaro	**Dr James Hopgood**
Dr Andy Harvey	**Prof Mervyn Jack**
Prof David Lane	**Dr David Laurenson**
Mr Ronald McHugh	**Prof Stephen McLaughlin**
Prof Yvan Petillot	**Prof Bernard Mulgrew**
Dr Neil Robertson	**Dr John Thompson**
Prof Andrew Wallace	
Dr Cheng-Xiang Wang	

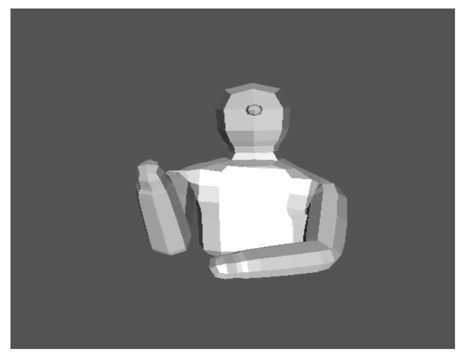
II. Research Areas and Projects

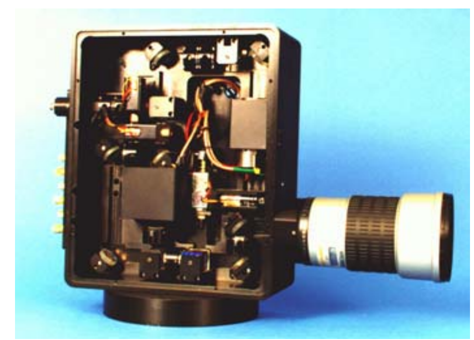
- Distributed sensing applications
- 2D, 3D image interpretation and beyond (hyperspectral, motion, complex)
- Image-world interaction: navigation, monitoring and surveillance
- Non-visible image processing, e.g., mm-wave, lidar, infrared …
- Algorithms for nonlinear & non-Gaussian signals and systems
- **Communications:**
    - **Wireless communications and networks**
    - Large scale wireless communication systems
    - Video conferencing and visual interfaces











Wireless Communications and Networks (1/2)

- Wireless Propagation Modelling and Simulation
  - For Analog (physical) Channels: real communication environment:
    - MIMO channels, ultra wideband (UWB) channels
    - Frequency diversity channels: FH, OFDM, and MC-CDMA
    - Mobile-to-mobile channels: vehicular communication networks, cooperative comm.
    - Channel simulators: deterministic and stochastic; sum-of-sinusoids based
  - For Digital Channels: a complete transmission chair including transmitter, analog channel, and receiver
    - Hard and soft error models; bit-level and packet-level error models
    - Deterministic process based generative models (DPBGMs)
    - Hidden Markov models

Wireless Communications and Networks (2/2)

- Cognitive radio networks:
  - Spectrum sensing, interference modeling, interference cancellation, capacity analysis, secondary network design, game theory applications
- Vehicular ad hoc networks (VANET)/vehicle-to-vehicle communications
- Cross-layer optimisation of wireless networks: (non-)convex optimisation
  - Physical layer: rate adaptation (adaptive modulation and coding)
  - Data link layer: opportunistic scheduling, power control, HARQ
- Cooperative (relay) communications: distributed MIMO/beamforming
- (Multiuser) MIMO, OFDM, MIMO-OFDM, UWB
- Mobile ad hoc networks, mesh networks
- 4G wireless mobile communications and beyond

Example Project 1: Comparison of MIMO Channel Models (3GPP SCM and KBSM) --Supported by BenQ Mobile (Siemens-Mobile Phones)

- **Problem description**:
  - **3GPP Spatial Channel Model (SCM):**
    - The space-time correlation (STC) properties are implicit. Difficult to connect SCM simulation results with theoretical analyses.
    - The implementation complexity is high since it has to generate many parameters.
  - **Kronecker-based stochastic model (KBSM):**
    - Elegant and concise analytical expressions for MIMO channel spatial correlation matrices → easy to be integrated into a theoretical framework!
    - Less input parameters. Has the KBSM been oversimplified?
  - **Open issues:**
    - What is the major physical phenomenon that makes the fundamental difference of two models?
    - Under what conditions will two models exhibit similar STC properties?

Research Findings: SCM vs. KBSM

- **Fundamental differences between the SCM & KBSM:**

	Num. of subpaths	AoA-AoD correlation
SCM	Finite (20)	Correlated
KBSM	Infinite (Gaussian process)	Independent

- **Equivalent conditions:**
  1. The number *M* of subpaths in each path for the SCM tends to infinity.
  2. Two links share the same antenna element at one end, i.e., at either the MS or the BS.
  3. The same set of angle parameters including the same PAS are used.
- The KBSM has the advantages of simplicity and analytical tractability, but is restricted to model only the averaging effects of MIMO channels.
- The SCM is more complex but provides more insights of the variations of different MIMO channel realizations.

C.-X. Wang, X. Hong, H. Wu, and W. Xu, "Spatial temporal correlation properties of the 3GPP spatial channel model and the Kronecker MIMO channel model", ***EURASIP Journal on Wireless Communications and Networking***, 2007. http://www.hindawi.com/GetArticle.aspx?doi=10.1155/2007/39871

Example Project 2: Error Models for Digital Channels and Applications to Wireless Communication Systems --Supported by Siemens AG-Mobile Phones; EPSRC & Philips

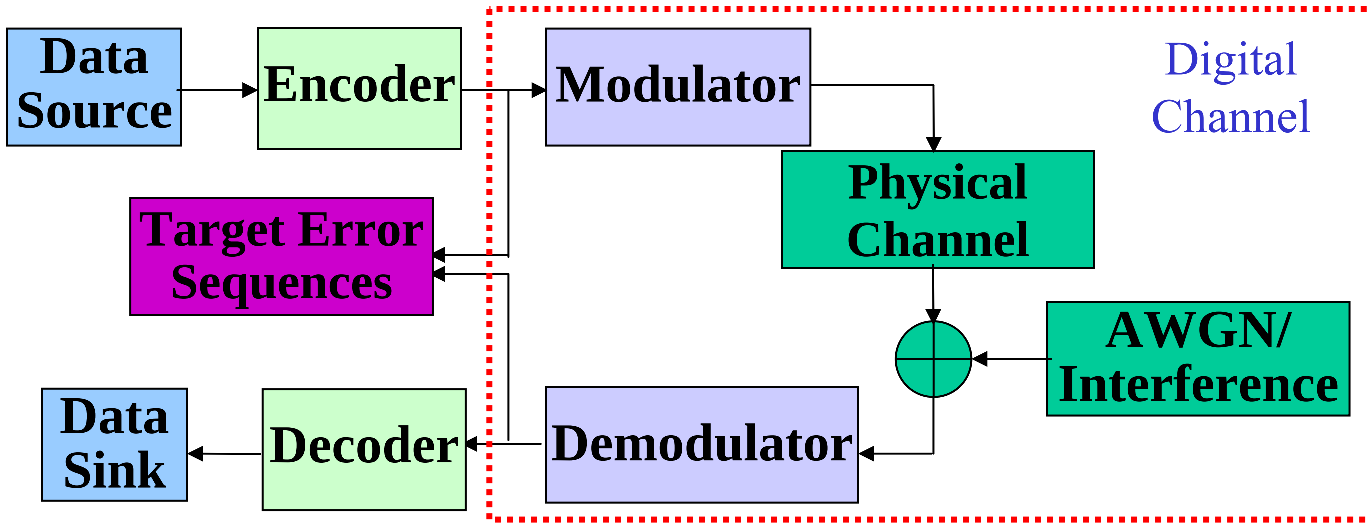
- It is a really time-consuming job to simulate the physical layer.
- Usually, the whole physical layer can be replaced by error sequences corresponding to different channel conditions and different physical layer techniques in the simulation of higher layer protocols.
- Numerous long error sequences are necessary to be generated and stored in the computer for future simulations of higher layer protocols.

$\Rightarrow$ **Fast error generation mechanisms should be developed**!

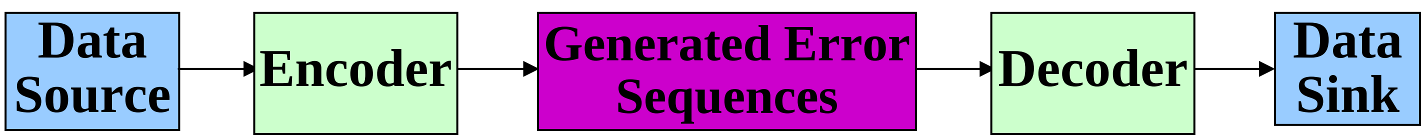
- Error sequence $\{e_k\}$: the difference between the input sequence and the output sequence of the digital channel, either bit level or packet level.
  - Hard error sequence: $e_k \in \{0,1\}$, k is a nonnegative integer
  - Soft error sequence: $e_k \in [-2^{M-1}, \quad 2^{M-1}-1]$, M is a positive integer
- Channel models for characterizing bursty error sequences encountered in digital mobile radio channels are called error models.

Error Models: Digital Channel Models

- Descriptive model (reference model): Analyzes burst error statistics of target error sequences obtained directly from experimental results.

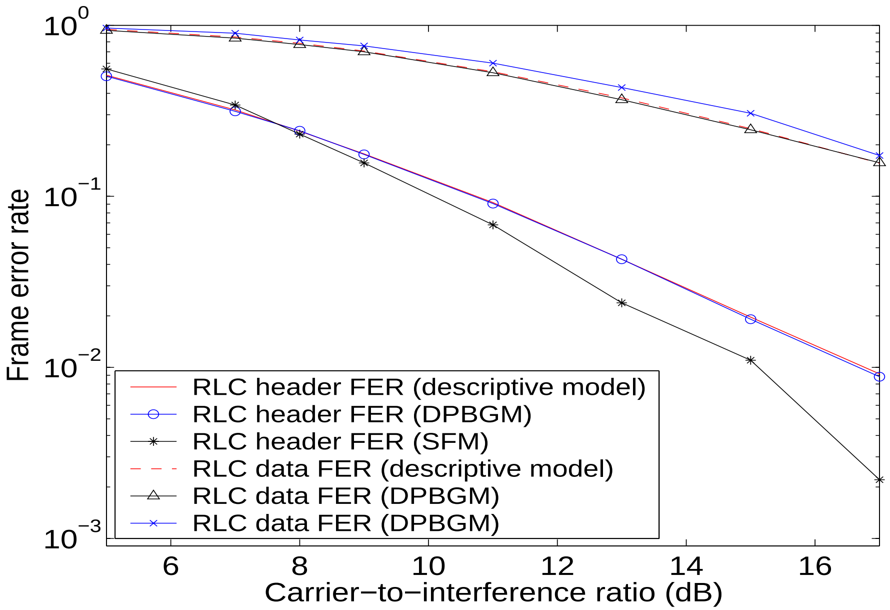


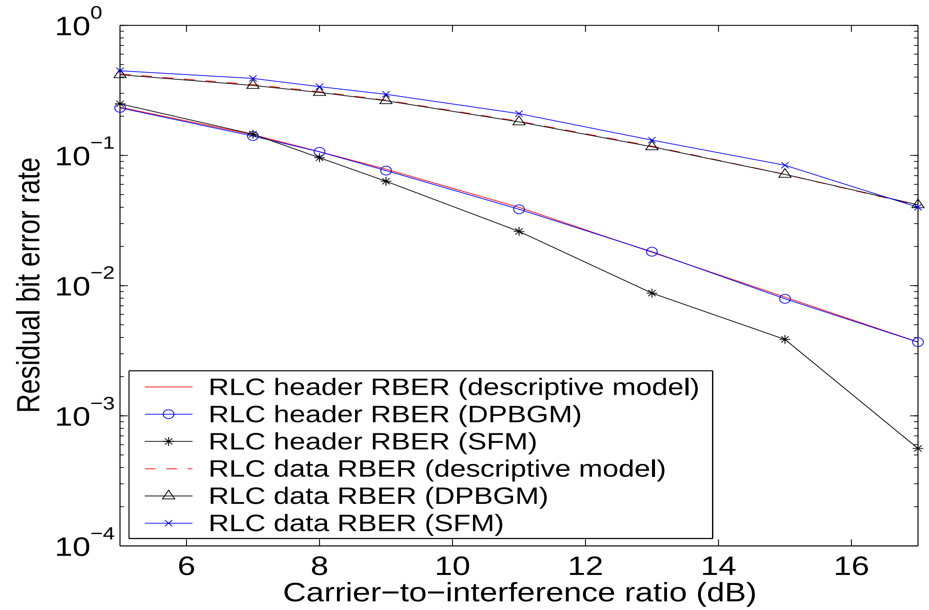
- Generative model (simulation model): Specifies an underlying mechanism that generates error sequences statistically similar to the target error sequences.
  - **Advantage**: speeds up simulations.



Research Outcomes

- Developed deterministic process based generative models (DPBGMs) and hidden Markov models (HMMs)





C.-X. Wang and W. Xu, "A novel generative approach to speed up performance simulations of wireless communication systems", **invention report**, Siemens AG, Munich, Germany, registration number: 2004E05718 DE.

C.-X. Wang and W. Xu, "A new class of generative models for burst error characterization in digital wireless channels," *IEEE Trans. Communications*, vol. 55, no. 3, pp. 453-462, March 2007.

O. S. Salih, **C.-X. Wang**, and D. I. Laurenson, "Three-layered hidden Markov models for binary digital wireless channels," *Proc. IEEE ICC 2009*, Dresden, Germany, June 2009

O. S. Salih, **C.-X. Wang**, and D. I. Laurenson, "Soft bit error modeling for discrete wireless channels," *Proc. IWCMC 2009*, Leipzig, Germany, 21-24 June 2009

Example Project 3: Interference Cancellation for Green Radio Networks --Supported by the EPSRC & Mobile VCE Core 5 Green Radio

- Green Radio:
  - Efficient wireless backhaul
  - Low energy wireless: delivery of higher data rates at 100* less power
  - Spectrum aware wireless: autonomous optimisation of spectrum usage, for energy efficiency and for quality of experience

- Main Work:
  - Study efficient receiver interference cancellation techniques
  - Exploit cooperation techniques to aid in interference suppression
  - Methods to estimate performance gains of interference cancellation to report back to the wireless network

III. Suggested Collaboration Topics for Collaborations

1. MIMO Channel Modelling, Simulation, and Measurement for 4G
2. Cognitive Radio Networks
3. Cooperative MIMO
4. Vehicular Communication Networks
5. Cross-Layer Optimisation (Radio Resource Management) of 4G Wireless Networks

1. MIMO Channel Modelling, Simulation, and Measurement for 4G

- **Existing MIMO channel models**: COST273, COST259, Winner, 3GPP SCM & wideband SCM, LTE, LTE-Advanced
- **Problems** to consider:
  - Is the standard MIMO channel model too complex/simplified and sufficiently adaptive?
  - Effect of different channel models on the MIMO system performance?
  - Future MIMO channel models: 1) Birth-death process 2) Multiple scatterers 3) Space-time-frequency correlation properties (application to MIMO-OFDM) 4) 3-D channel models
- **Channel simulator**: 1) Accuracy 2) Simulation efficiency 3) Flexibility/Adaptability
- **Measurements**: 1) understand physical phenomenon 2) test channel models

2. Cognitive Radio Networks

- **Key benefits**:
  - Provide effective platforms to integrate multiple radio interfaces; Improve cellular spectrum efficiency
  - Compliment the 4G cellular spectrum by borrowing/reusing the underutilized spectrum from other radio systems
- **Proposed research**:
  - **Interference modelling and channel characterisation**
    - 3-D (space/time/frequency) white space modelling
    - Inter-system (primary-secondary) interference modelling; Intra-system interference modelling
  - **System capacity analysis**
    - Average/peak/outage interference power constraint
    - System architecture (centralized, ad-hoc)
    - Multiple access and radio resource allocation schemes
  - **Interference cancellation**
    - Transformed domain approach; Cyclostationarity-based approach; Spatial processing
- **Publications**: 1 book chapter, 4 journals, 3 journal submissions, 7 conferences

3. Cooperative MIMO

- Background
  - Key benefits to 4G systems
    - Combat fading and shadowing
    - Mitigate multi-cell interference
  - Classifications of cooperative MIMO
    - Between multiple base stations (BSs)
    - Between multiple mobile devices
  - Technical challenges
    - Cooperation protocols with reduced signalling overhead
    - Cooperation protocols robust to unreliable channel information
    - Realistic and computation-efficient multi-cell MIMO channel models
    - System level (multi-cell) performance evaluation of cooperative MIMO schemes

Cooperative MIMO (cont.)

- Proposed research topics
  - Multi-cell MIMO channel modelling
    - Correlation model for large scale fading across multi-cells
    - Mobile to mobile channel modelling
    - Parametric/hybrid system level channel models with high computation efficiency
  - Robust multi-cell interference cancellation
    - Distributed multi-cell beamforming and precoding
    - Distributed multi-cell resource allocation
  - Low-complexity cooperative diversity scheme
    - Performance-complexity trade-off
    - Quantization and feedback of channel state information

4. Vehicular Communication Networks

- **Applications**: safety (e.g., automatic collision warning) and non-safety applications (automobile Internet access).
- Both the Tx and Rx are in motion and equipped with low elevation antennas.
  - Differ from conventional fixed-to-mobile (F2M) cellular radio systems in terms of channel characteristics, especially Doppler effects.
- MIMO technology is very promising for vehicular communications since multiple antenna elements can be easily placed on large vehicle surfaces.
- **Research problems**:
  - Channel modelling, simulation, and measurement
  - Physical, link, and network layer technologies of vehicular networks
  - Cross-layer optimisation
- **Publications**: 1 JSAC SI (coming), 2 journals, 3 journal submissions, 5 conferences

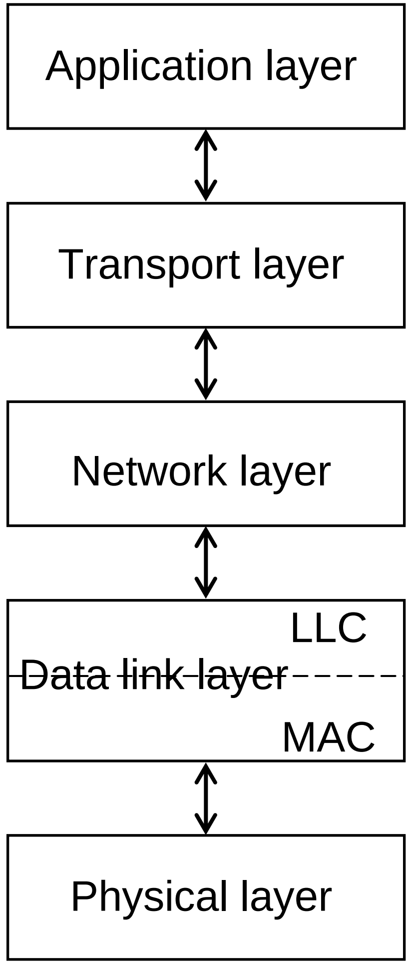
5. Cross-Layer Optimisation (Radio Resource Management) of 4G Wireless Networks

- **Traditional layered approach**:
  - The protocols at each layer are independently designed.
  - Layers are required to communicate in a strict manner → inflexible, no adaptation to dynamic wireless environments

  ⇒ Easy for design, but poor system performance and inefficient use of valuable resources (power, spectrum)

- **Cross-layer design**:
  - Layers are coupled ← due to power constraints, delay constraints, error performance constraints, etc.
  - Jointly optimises protocols by taking advantage of the interaction across different layers.

  ⇒ Significant performance improvement and efficient use of resources but increased design complexity



The Proposed Cross-Layer Design Approach

- The optimisation of the entire network layers simultaneously is very complex and requires near brute-force simulation efforts.
- **Focus**: joint optimisation of the PHY layer and link layer of wireless ad hoc networks.
- **Aim**: to develop a novel and efficient cross-layer design approach
  - PHY layer: rate control through adaptive coding; error modelling techniques
  - Link layer: power control, scheduling, ARQ
- Error models will be applied to improve simulation efficiency.
- **Optimisation criterion**: to maximize the spectral efficiency (throughput) of wireless ad hoc networks under the prescribed power, delay, and error performance constraints.