CHEDDAR

Cranfield University

UKRI Engineering and Physical Sciences Research Council

Federated Telecoms Hubs

Guarantee Stability in Base Station Traffic Load Balancing Using Impulsive Network Dynamics

Theme: Emerging Technologies & Frontier Communication

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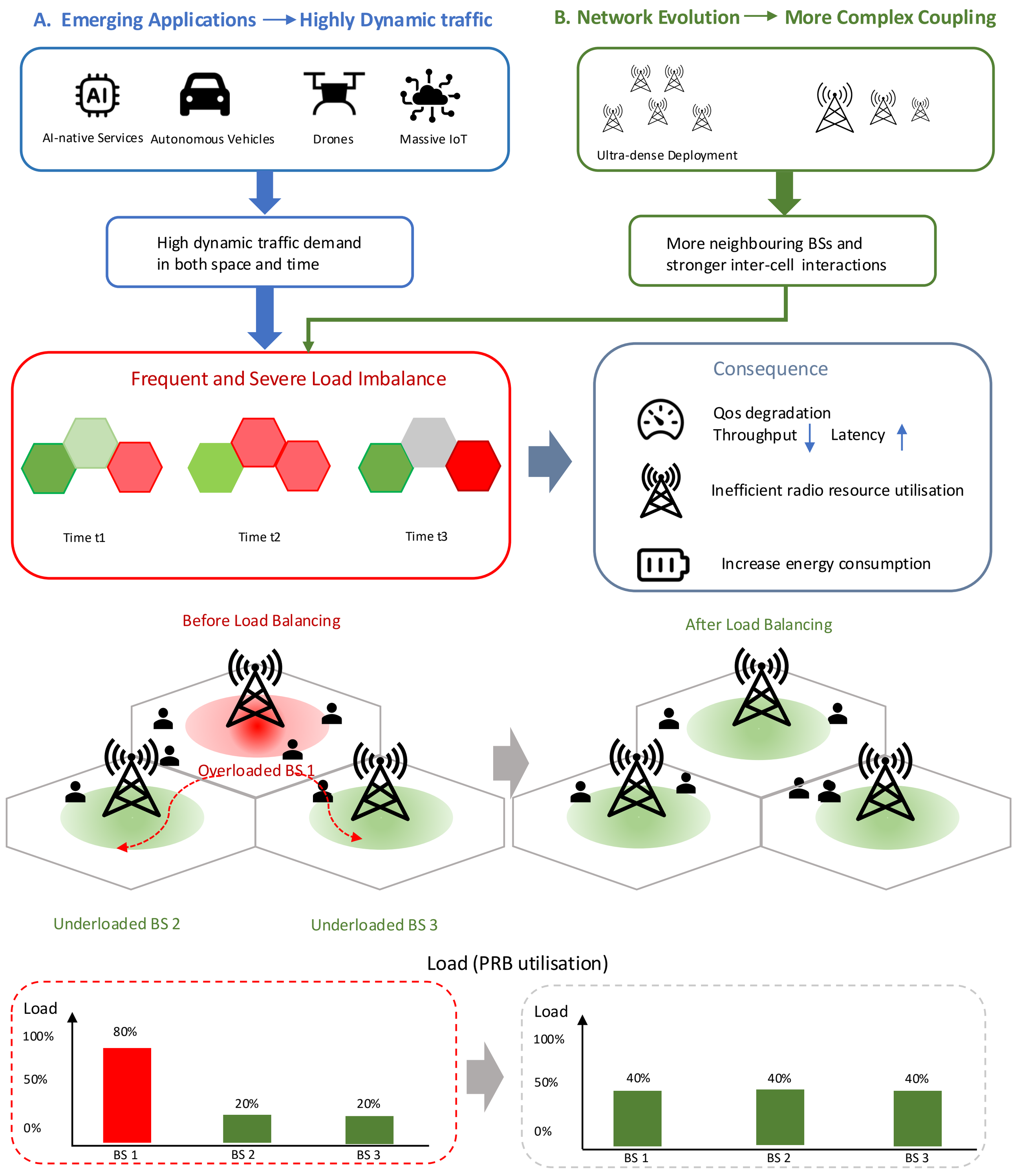
Background and Research Gap

Background

Load balancing aims to redistributed users from overloaded base stations (BSs) to neighbour BSs so that network capacity is efficiently utilised and that spike demands are met by sharing the load. In 6G, ultra-dense deployments of BSs and diverse services make traffic highly dynamic and load interactions more complex, so efficient and stable load balancing is more critical than ever.



Research Gap

-- Limitation of Existing Methods

- Rely on instantaneous or historical load information to control CIO to hand over users.
- Lack a theoretical model for long-term load evolution to provide the foundation of theoretical analysis.
- Cannot explain oscillations or guarantee stability to ensure the performance in long term.

Contribution

1. Dynamic Modelling
   - Build the two-timescale impulsive network dynamics model for load evolution
   - Links physical layer parameters to load evolution
2. Theoretical Analysis
   - Explain when load balancing converges and maintain stable and why oscillation happens and cause the ping pong
   - The theoretical analysis can guide the design of handover mechanism
3. Algorithm Design
   - Design a dynamics-guided load balancing algorithm

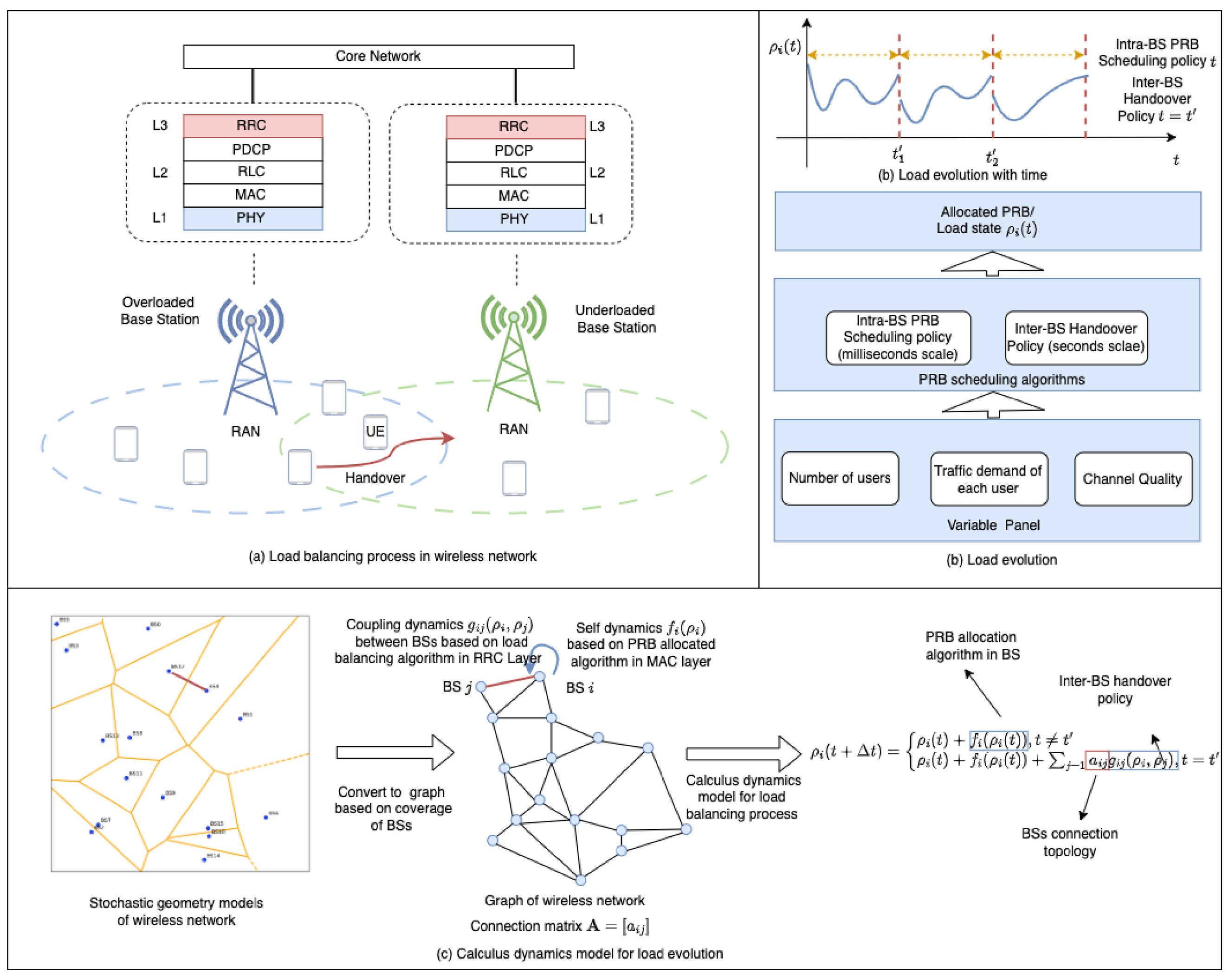
Methodology

1. Establish a two-timescale impulsive network dynamics for load evolution:

$$\rho_i(t+\Delta t) = \begin{cases} \rho_i(t) + \dfrac{f_i\left(\Delta B_i^{\mathrm{req}}(t), \rho_i(t)\right)}{B_i^{\mathrm{total}}}, & \text{only intra PRB scheduling} \\ \rho_i(t) + \dfrac{f_i\left(\Delta B_i^{\mathrm{req}}(t), \rho_i(t)\right)}{B_i^{\mathrm{total}}} + \sum a_{ij}\, g_{ij}\left(\rho_i(t), \rho_j(t)\right), & \text{handover happpens} \end{cases}$$

2. Theoretical analysis

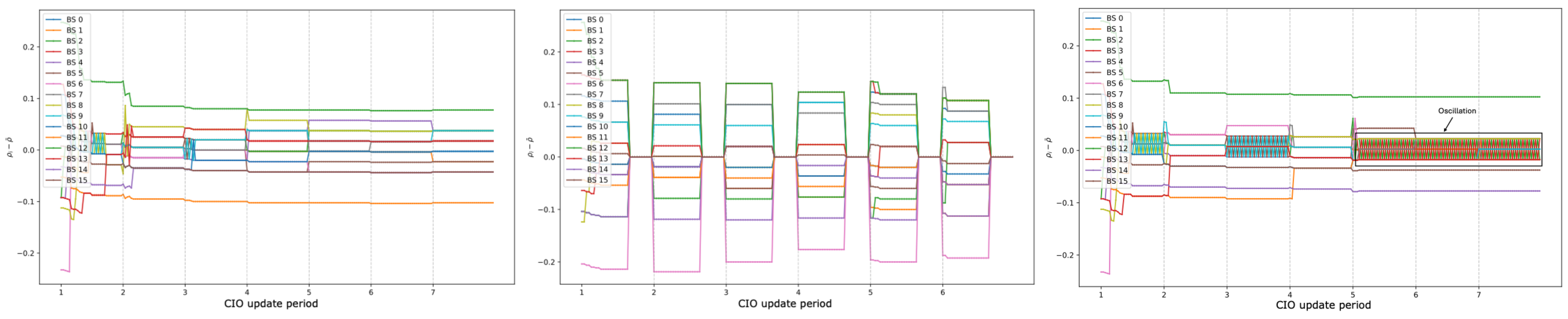
- Derive stability and bounded synchronisation conditions.
- Characterise the effects of dynamics eigenvalues and load transfer errors on the synchronisation bound.
- Show that asymmetric load transfer can induce oscillations and ping-pong handovers.



3. Algorithm Design

- Use the theoretical results to guide load transfer design to control CIO and oscillation mitigation mechanism.

Results



- When the derived synchronisation conditions are satisfied, the BS loads converge to the desired balanced state and remain stable over time.
- The proposed algorithm effectively mitigates oscillatory behaviour, thereby reducing unnecessary handovers and ping-pong events.
- Compared with heuristic methods, the proposed approach achieves better load balancing performance. It also achieves comparable or better load balancing than RL-based methods in many scenarios while requiring fewer handovers.

Users	Algorithm	Number of HO	Ping Pong
300	1 (proposed)	27	1
	2 (heuristic)	34	0
	3 (DQN)	56	5
400	1	34	0
	2	54	3
	3	78	14

Conclusion and Future Work

- Developed a dynamics framework for analysing cellular load balancing.
- Revealed the causes of oscillation and derived stability conditions.
- Designed a theory-guided algorithm to improve load balancing performance.
- Verified the proposed framework through simulations.

In the future, we will deploy the proposed method in O-RAN testbeds.

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