RF Environment Modelling Techniques for Heterogeneous Network Management

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Overview

- RF Environment
- Graph Theory
- Hypergraph Theory – Concept and Related Works/Applications
- Hypergraph-based Modelling – Concept Studies (2)
- Future Innovations and Applications
- Conclusion

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RF Environment

- **Definitions**
  - Radio devices and networks that are operating in a given spectrum band, in a given location at a given time.
  - Model – representation of how device/system parameters and spectral parameters interact – relationships
  - Modelling at storage layer and at application layer.

- **Spectrum Management Shifts**
  - Static to dynamic spectrum assignment
  - Licence-exemption/GAA – equal access rights /sharing in the time domain
  - Homogeneous to heterogeneous usage and access

- **Modelling of multiple relationships**
  - Network dependency
  - Cumulative interference
  - Spectral coexistence
  - Coexistence groups

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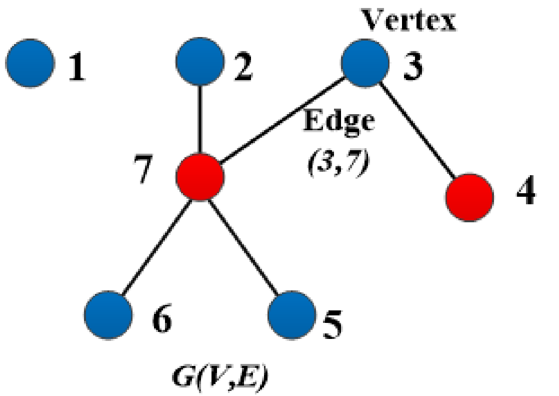
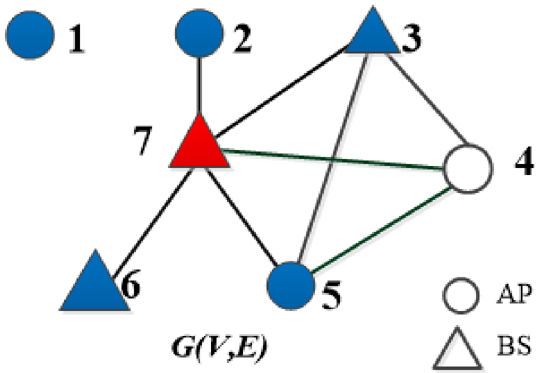
Graph Theory

- **Graph Model**
  - An edge is a two-element connection
    - e.g. used to model one-way/mutual interference
  - Graph colouring algorithms used to solve channel assignment quadratic time complexity



- **Advantage**
  - Suitable for exclusive channel allocation
  - Relatively less complex – quadratic time complexity (O(n2))



- **Limitations**
  - An edge not suitable for modelling multiple relationships
  - Suitable for modelling in frequency and space, but not in time as well [1].
  - Spectrum time-sharing is limited by previous allocations [2].

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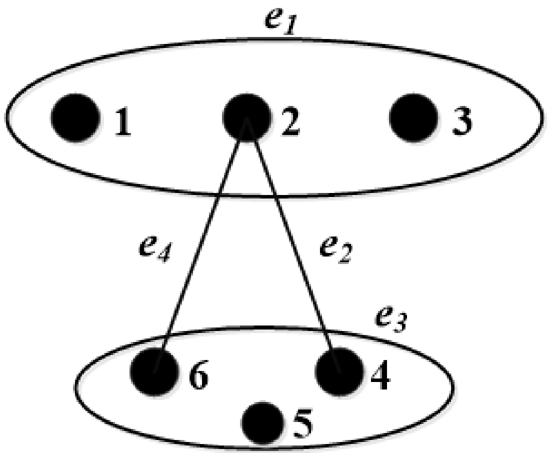
Hypergraph Theory

- **Hypergraph**
  - is a generalisation of an undirected graph in which a hyperedge is a subset of arbitrary number of vertices [3].
  - Hyperedge can represent multifaceted relationships.
  - Sufficient to model complex/multiple relationships at the same time, in one data structure.



H(X,E)

	e_1	e_2	e_3	e_4
1	1	0	0	0
2	1	1	0	1
3	1	0	0	0
4	0	1	1	0
5	0	0	1	1
6	0	0	1	0

I(H)

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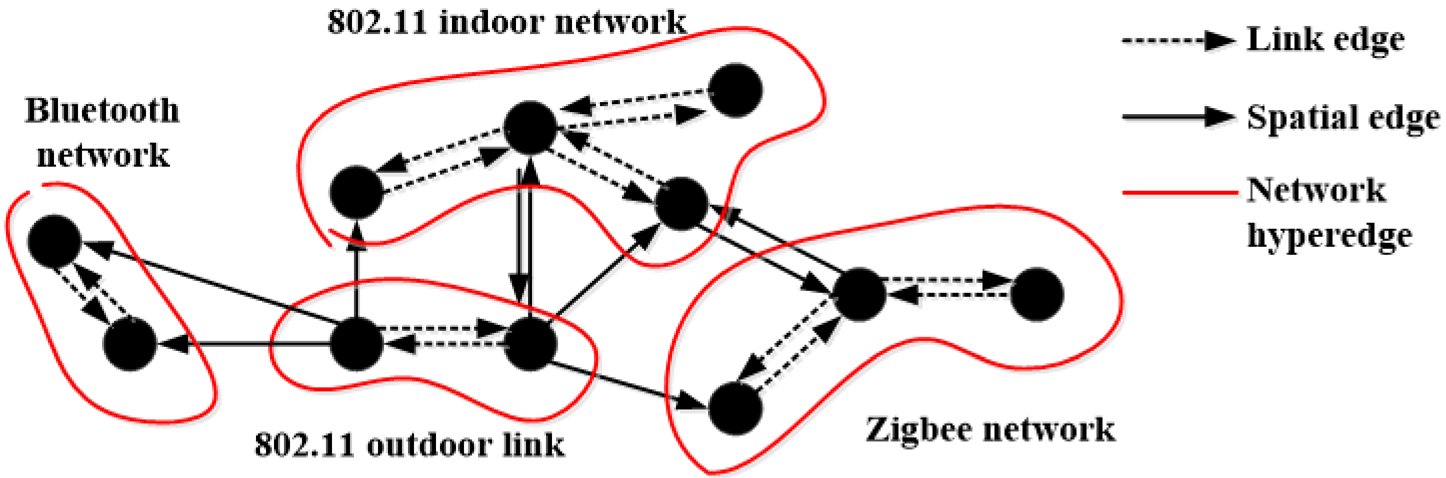
Related Works on Hypergraph in Coexistence Management (1)

- **Network Dependency**

− A hypergraph used to represent the RF environment structure to provide constraints for spectrum assignment [4].

− A hyperedge represented a group of networks that belong to the same network and therefore need to be assigned the same channel.



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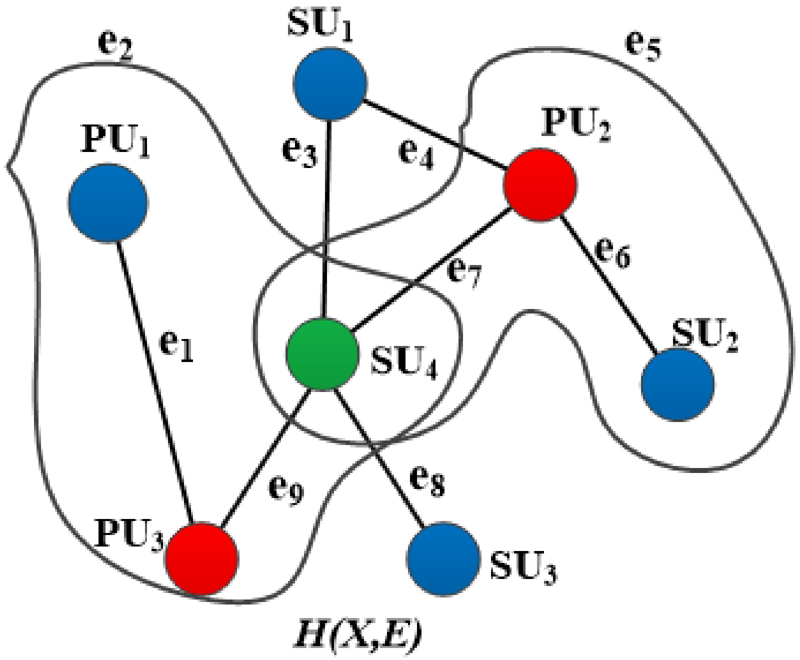
Related Works on Hypergraph in Coexistence Management (2)

- **Cumulative Interference**
  - A hypergraph used to represent one-way/mutual interference and cumulative interference [5].
  - A hyperedge represented a group of radio devices that are cumulative interferers.
  - Strong hypergraph used to model radio resource allocation.
  - Result: Improved system capacity due to mitigation of cumulative interference.
  - Drawback: Computational complexity – cubic time complexity ($O(n^3)$)



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Concept Study 1 – Modelling Spectrum Sharing

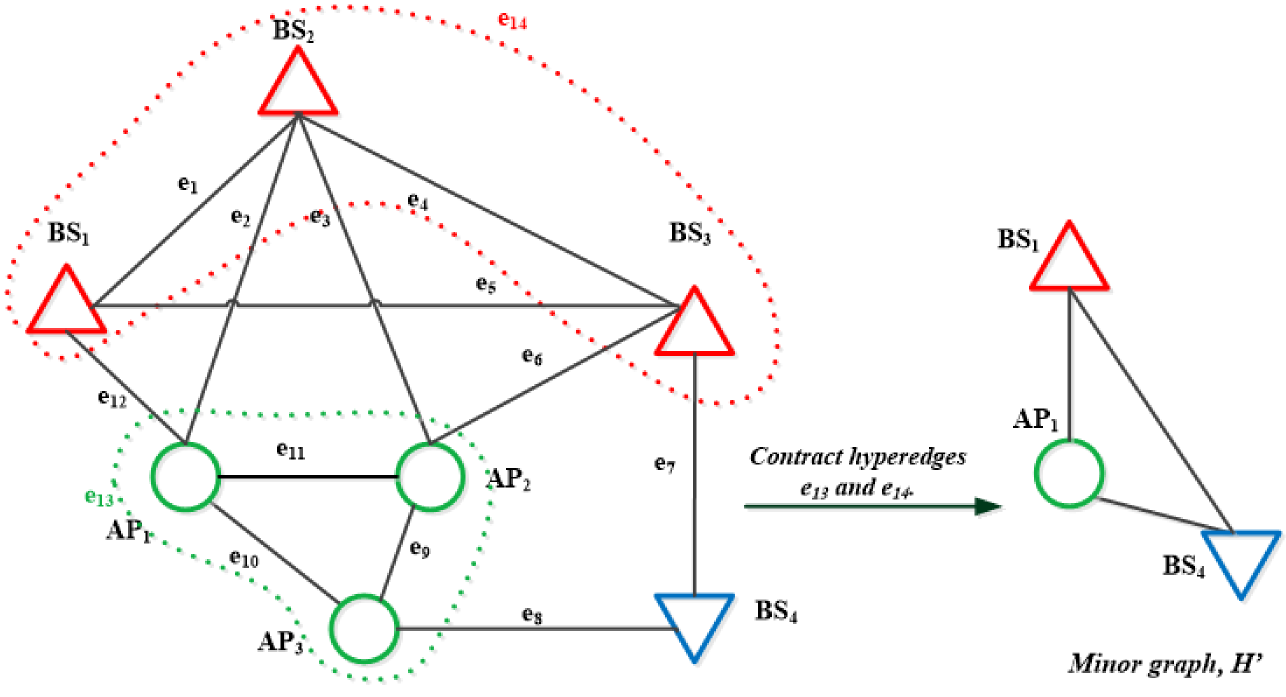
- **Spectrum Allocation on Sharing Basis in Time Domain [6][7]**

− Spectral coexistence model based on IEEE 802.19.1 method for “co-sharing based on network geometry”.

− Channel load was considered in constituting co-sharing network groups

− Edge represents interference relationship and hyperedge represents co-sharing networks

− Hyperedge contraction to reduce hypergraph to the form of a normal graph



Hypergraph, H

Minor graph, H’

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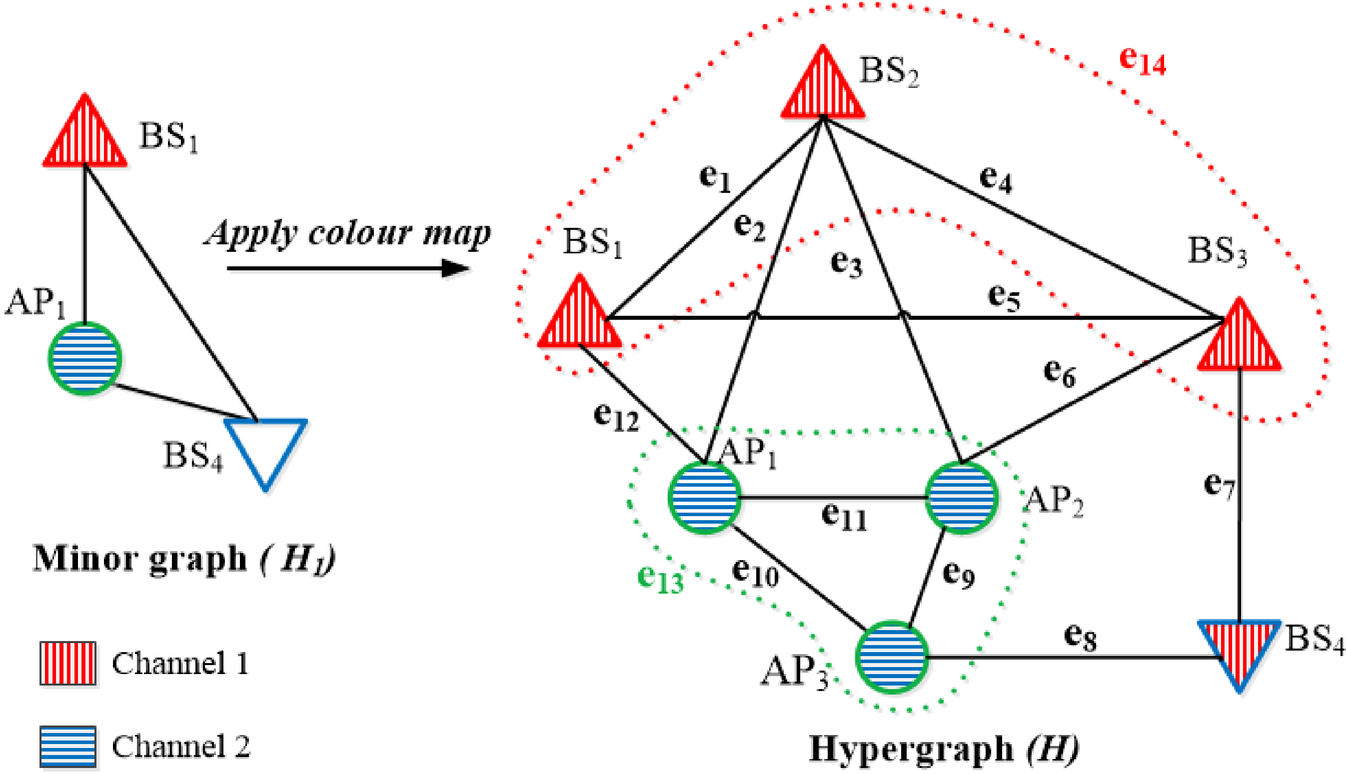
Concept Study 1 – Modelling Spectrum Sharing

- **Spectrum Allocation on Sharing Basis in Time Domain**
  - Graph colouring of minor graph is used to generate colourmap used to colour the hypergraph.



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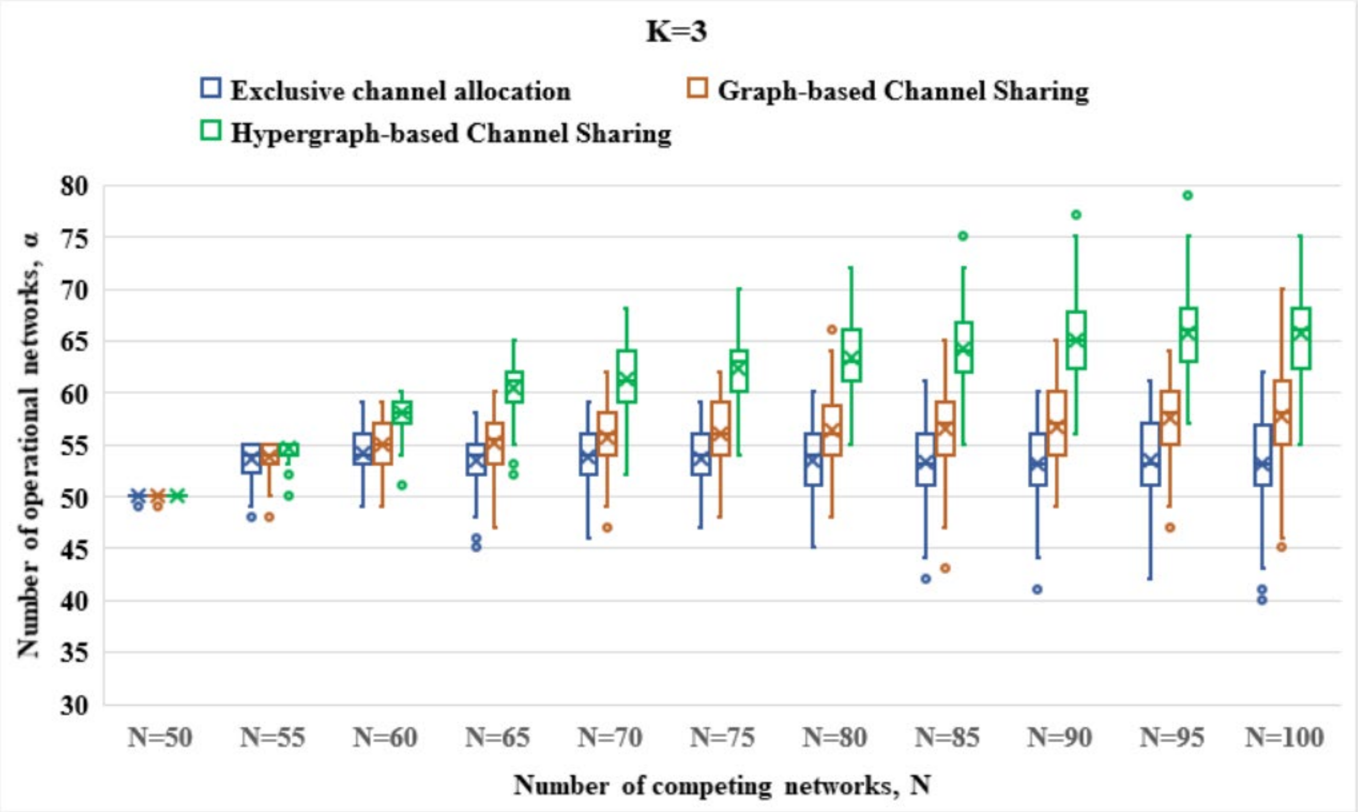
Concept Study 1: Results - 1

- **Efficient spectrum utilisation**

  - Performance metric: Percentage of operational networks
    - Graph-based: 58%
    - Hypergraph-based: 66%



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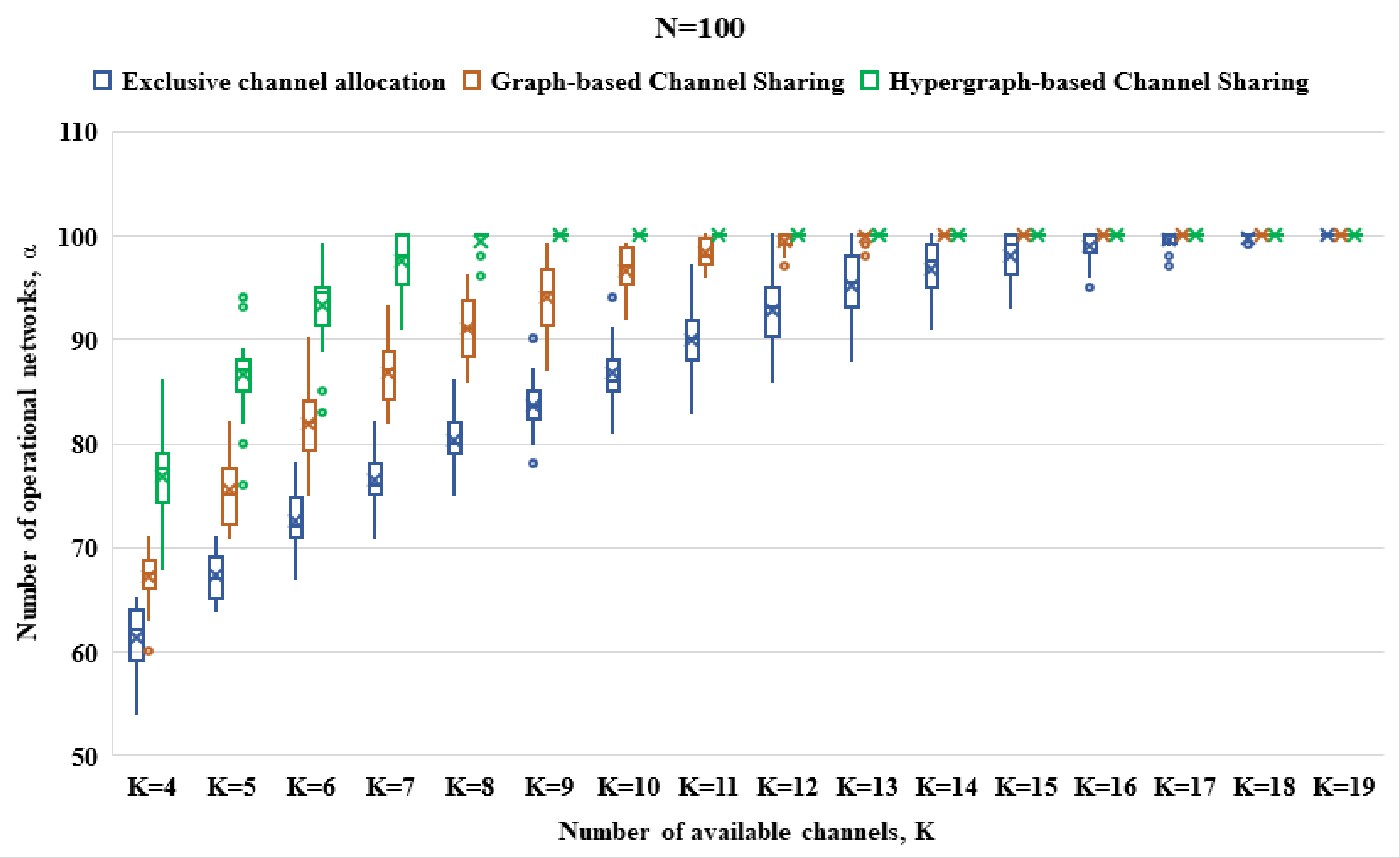
Concept Study 1: Results - 2

- **Efficient spectrum utilisation**

– Performance metric: Number of channels required for, on average, 100% operational networks.

  – Graph-based: 14 channels

  – Hypergraph-based: 9 channels



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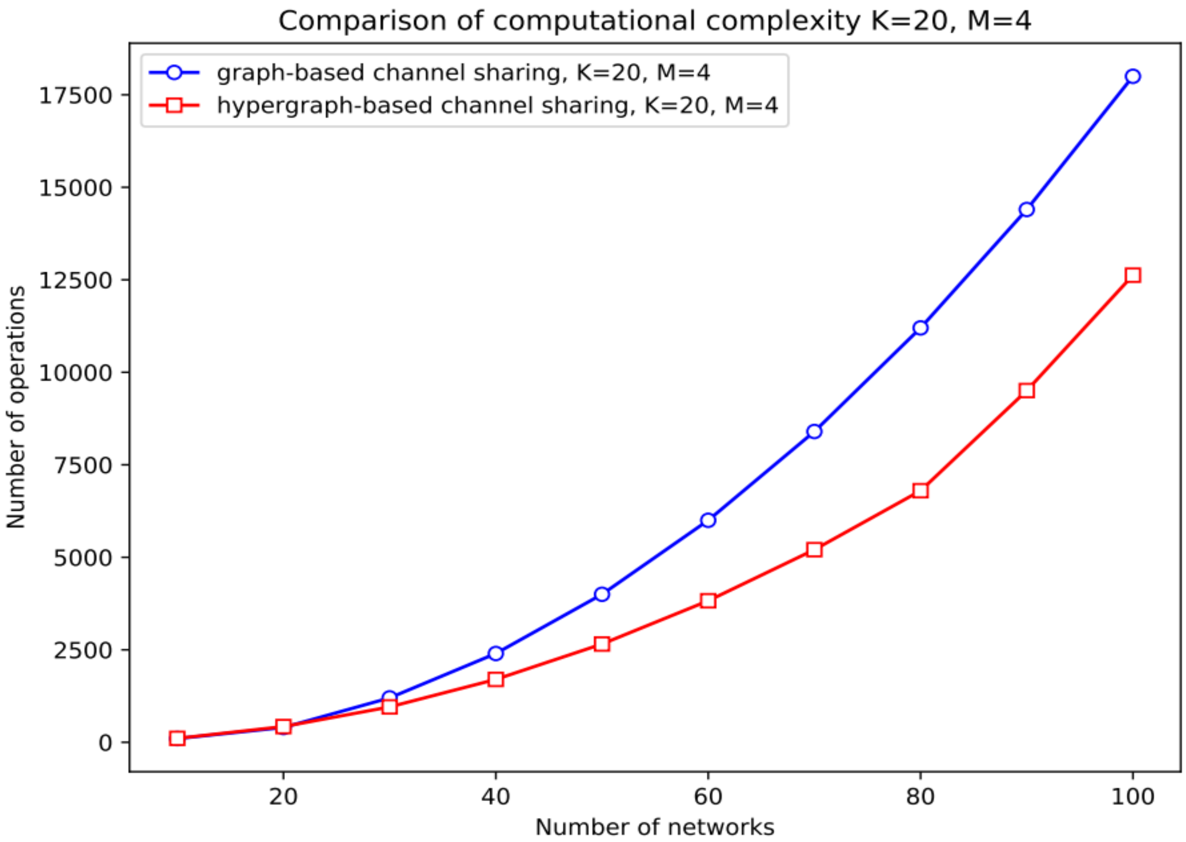
Efficient Computational Complexity

- **Performance criteria: time complexity (O(n))**

− Quadratic time complexity – comparable to graph-based model

− Potential for reduced time complexity due reduced input size after hyperedge contraction, depending on:

  – The number of interference coordination groups and number of elements in the groups (M)
  – The number of available channels (K)



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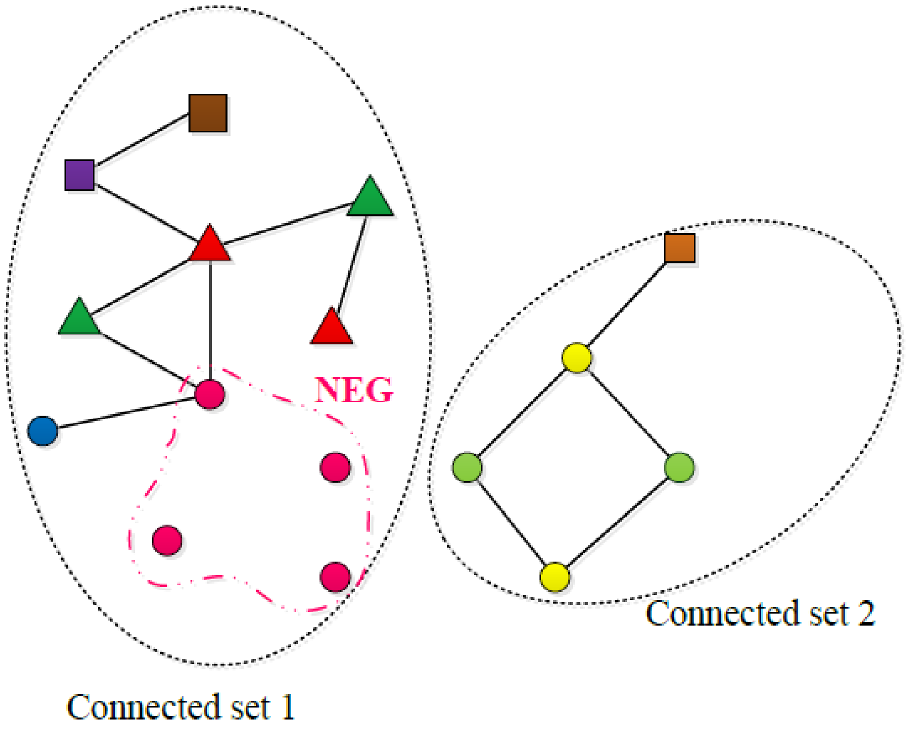
Concept Study 2: Bandwidth Allocation – Graph-based

- **GAA Spectrum Coordination Approach 1**

− Inter-Coexistence Group coordination

− No Edge Groups – can coordinate interference among themselves.

− Graph colouring to compute chromatic numbers for calculating bandwidth allocation.



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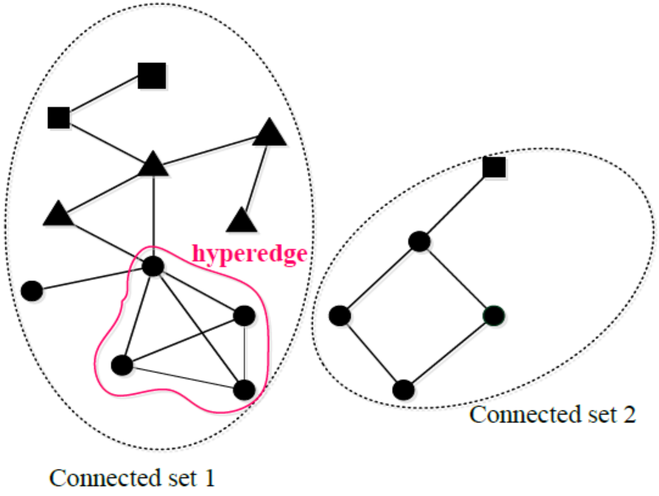
Concept Study 2: Bandwidth Allocation – Hypergraph-based

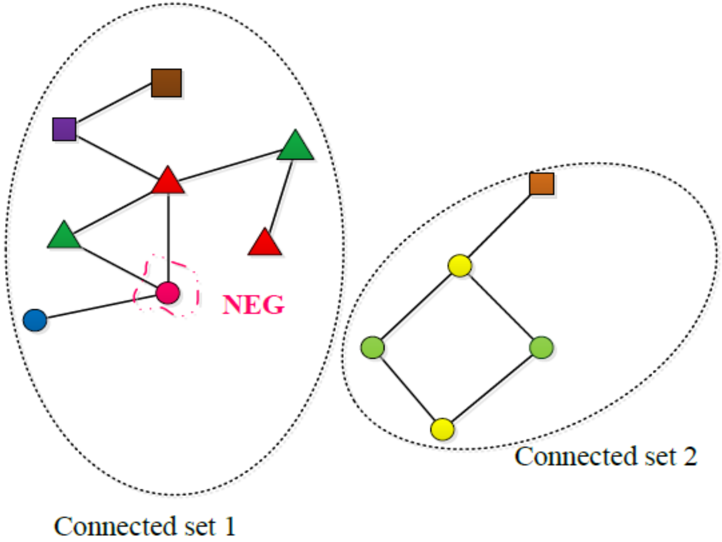
- **GAA Spectrum Coordination Approach 1**

− Hyperedge represents No Edge Groups

− Hyperedge contraction to reduce hypergraph to the form of a normal graph with fewer nodes than the original interference graph => reduces computational complexity.

− Graph colouring to compute chromatic numbers for calculating bandwidth allocation.





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Suggestions for Future Innovations and Application

- **Automated Dynamic Network Management – coexistence management and spectrum allocation**
  - **RF Environment Knowledge Database**

− For coexistence information or for learning database

− Database based on Hypergraph data model e.g. TypeDB

− Relationships are first-class constructs, can have meta-data.

− Reduces complexity of data retrieval

  - **Automated Dynamic Network Management**

− Cumulative interference mitigation, coexistence management and spectrum coordination form part of network management.

− Algorithms for multifaceted radio resource allocation.

− Reduction of computational complexity

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Suggestions for Future Innovations and Applications

- **Dynamic Spectrum Management**
  - “Use it most of the time or time-share it”
  - Spectrum sharing at a guaranteed contention ratio.
  - Spectral coexistence modelling.

- **Frequency Planning**
  - the number of channels that are required to maintain a target level of network capacity or the number of networks that can be supported by the number of available channels
  - Algorithms for radio resource allocation could be adapted for frequency planning .

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Conclusions

- Heterogeneous RF environments are characterised by multiple relationships
- Graph theory is not sufficient to model multiple relationships, but Hypergraph theory.
- However, the drawback is computational complexity
- Our work has shown that hypergraph-based model results in better spectrum efficiency than graph-based model at comparable computational complexity through hyperedge contraction.
- Future innovations could include applications for RF environment knowledge database, automated network management, dynamic spectrum management, and frequency planning.
- Future modelling tools could also include hypergraph-based algorithms and libraries for multi-faceted modelling and reduction of computational complexity.

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[7] T. Nyasulu and D. H. Crawford, “Comparison of Graph-based and Hypergraph-based Models for Wireless Network Coexistence," 2021 IEEE International Mediterranean Conference on Communications and Networking, Athens, Greece, 2021 (Accepted)

Thank You

- https://sdr.eee.strath.ac.uk/
- https://github.com/strath-sdr
- @StrathSDR