# IoT Network Engineering

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# IoT Networkt Engineering

*Goal:* To introduce the fundamental concepts behind the Internet-of-Things networks engineering with their applications to the developing world by

- Overviewing some of the emerging IoT network architectures and their deployment scenarios for the developing world.
- Looking at novel IoT network engineering techniques and old techniques and how they can be redesigned to fit in the emerging IoT networks.
- Presenting some of preliminary research results in IoT network engineering and discuss their impact on IoT deployments in the developing world.

# Motivation

- Recent move of UAVs/Drones into the environmental sensing and transportation fields has brought two new dimensions to the IoT field:
  - Airborne Data Muling/Ferrying [1]: e.g. Terabits of Bioinformatics data can be ferried from places to other places by drones using a number of flash disks, drones can play the role of "airborne gateways" used to collect data from terrestrial sinks.
  - Airborne Sensor Networking [2]: Besides a dual core processing unit with 8Gb of Ram, the cheapest drones are nowadays equipped with powerful cameras, GPS, Accelerometers and many other sensors making them powerful "airborne sensors".

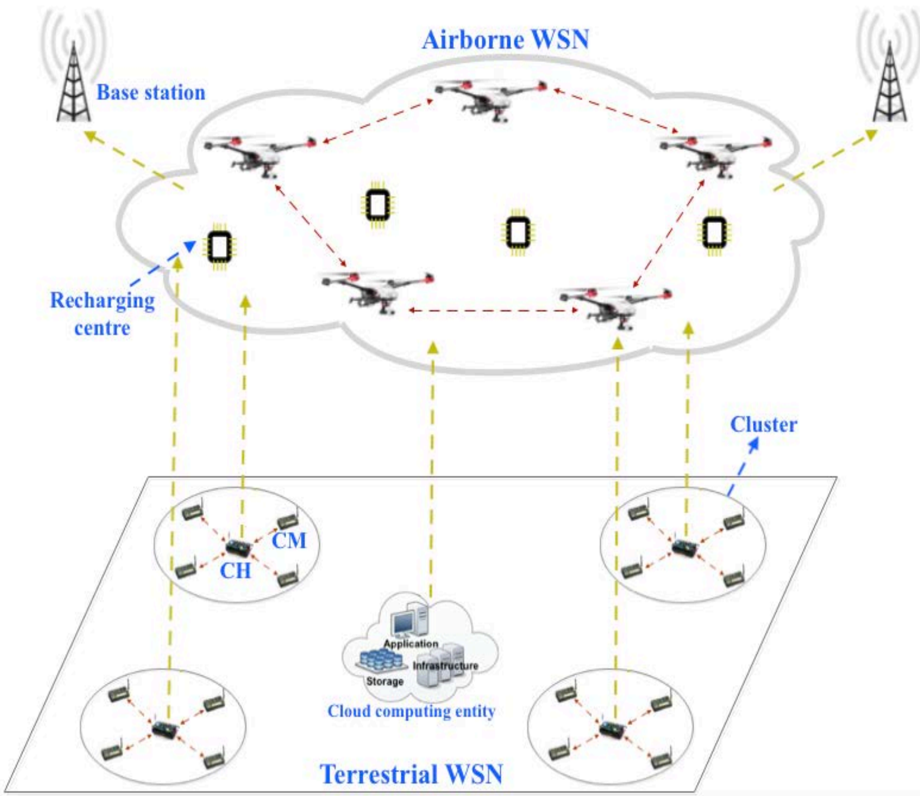
**[1] A.. Bagula, N. Boudriga and S. Rekhins, "Internet-of-Things in Motion: A Cooperative Data Muling Model for Public Safety ", in the proceedings of the 13th IEEE International Conference on Ubiquitous Intelligence and Computing (UIC), 2016.**
**[2] Soumaya Bel Hadj Youssef, Slim Rekhis, Nourredine Boudriga and Antoine Bagula, "A cloud of UAVs for the Delivery of a Sink As A Service to Terrestrial WSNs ", in the proceedings of the the 14th International Conference on Advances in Mobile Computing & Multimedia (MoMM2016).**

# Motivation

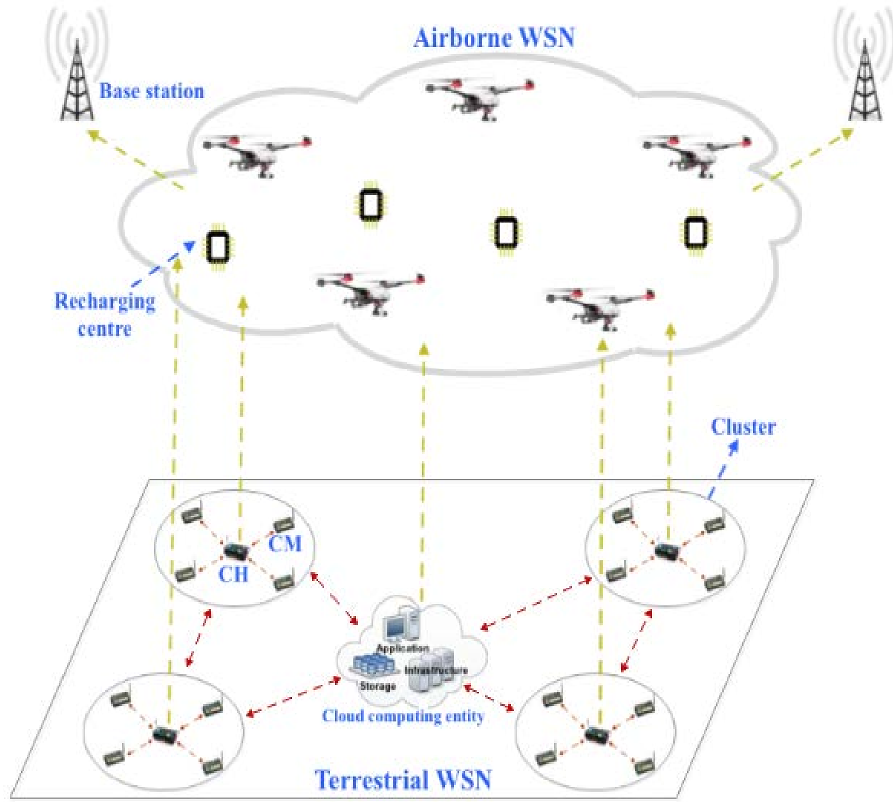
- Recent attempts by Google to provide Internet connectivity to rural and isolated areas of the world using air balloon have resulted in the model being replicated by UAVs/drones and a new dimension to wireless networking
  - Airborne Wireless Hotspots [3]: e.g. A quadcopter is equipped with 5G equipment to provide intermittent/opportunistic wireless communication to schools, church, hospitals, and municipalities rural and isolated areas of the world. Google's project Loon plans to bring internet access to remote locations via a network of high-altitude balloons. Internet.org is taking a similar approach, except instead of balloons, it envisions using drones as the delivery platform.

**[3] Luca Chiaraviglio et al, "Bringing 5G in Rural and Low-Income Areas: Is it Feasible?", IEEE Communications Standards Magazine, 2017**

# Emerging IoT Network Architecture

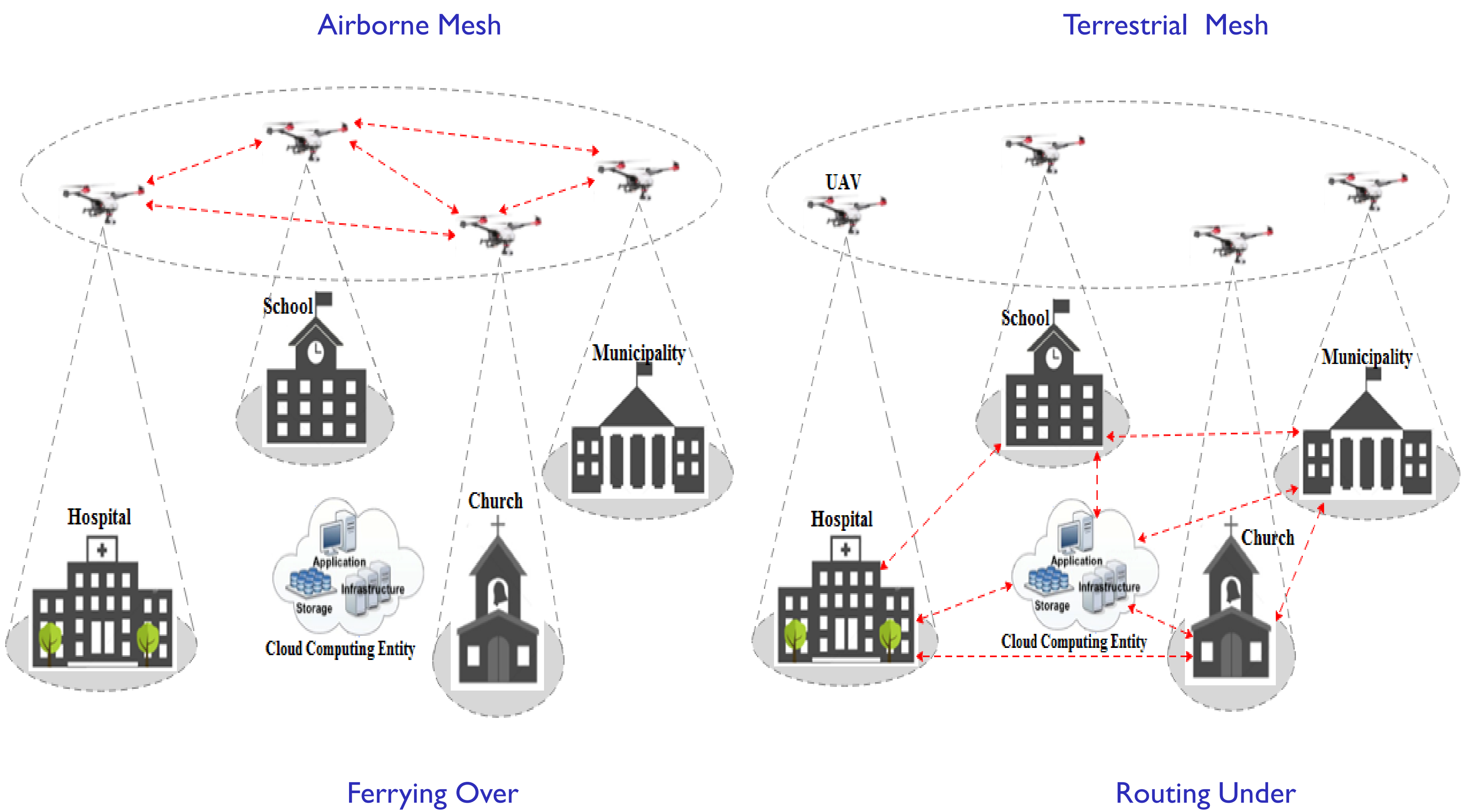



Airborne Mesh

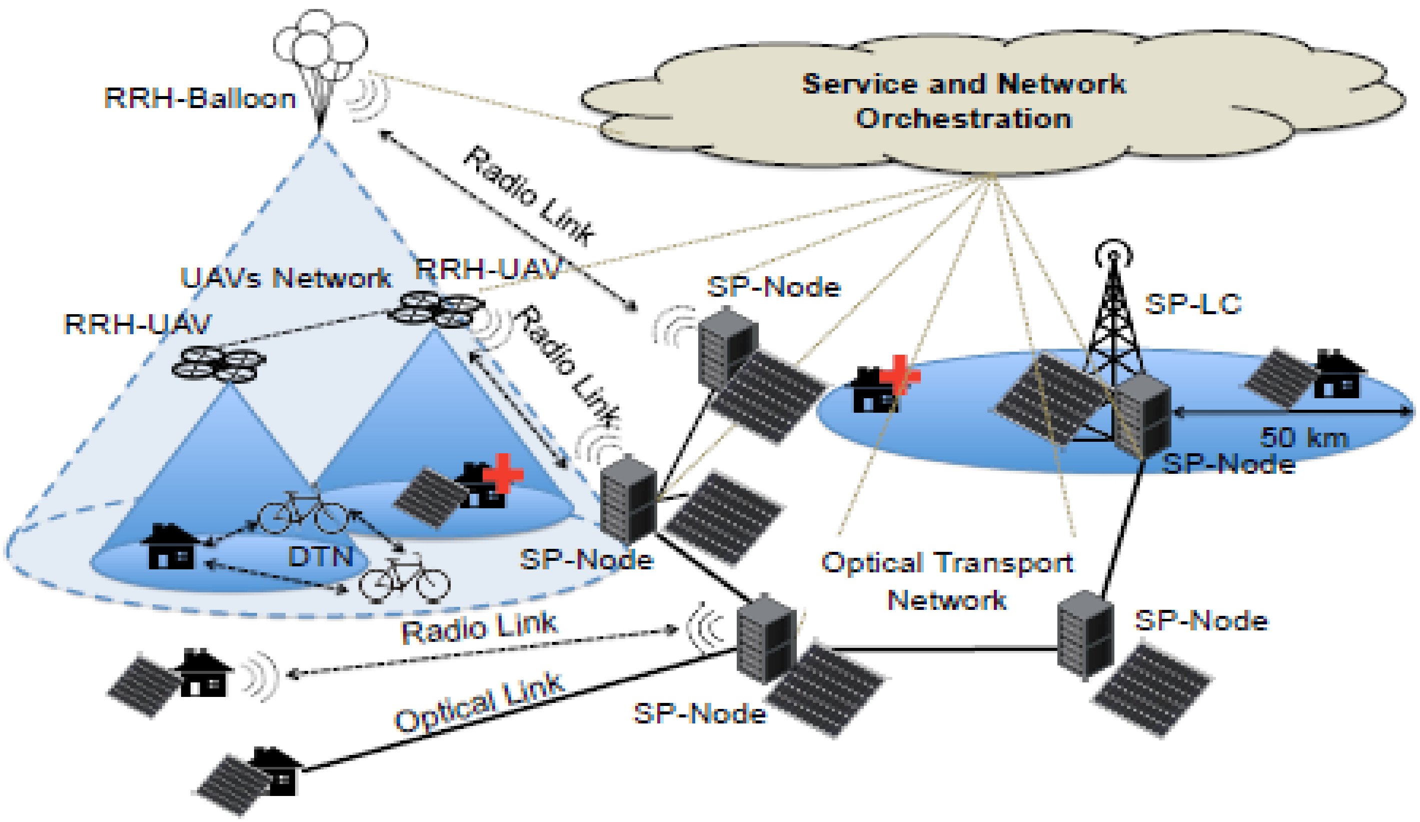



Terrestrial Mesh

# Emerging Deployment Scenario



# 5G Network for Rural and Isolated Areas




**SP = solar powered, LC = Large Cell, RRH = Remote Radio Head, UAV = Unmanned Aerial Vehicle, DTN = Delay Tolerant Network, NODE = Flexible component that can act as micro server, BBU, SDN switch and optical router.**

# 5G Network for Rural and Isolated Areas

## Pubblicato studio per la diffusione a basso costo della tecnologia 5G

# Internet ultraveloce volerà sui droni?

*Un pinerolese tra i ricercatori - Presa in esame l'area Scalenghe, Airasca, Piscina*

E attesa per il 2020, quindi è dietro l'angolo, l'immissione sul mercato della tecnologia 5G, che permetterà velocità di trasferimento altissime e nuovi modi di sfruttare il traffico dati, ma anche di connettere più persone e più dispositivi tra loro contemporaneamente (iperconnessione). Tecnologia che per essere fruibile richiede però forti investimenti infrastrutturali per cui molto spesso accade, lo sappiamo bene del Pinerolese, che le aree più disagiate e con pochi utenti vengano scartate dai gestori preoccupati di non aver garantito un adeguato ritorno economico.

Per ovviare a questo inconveniente un gruppo di ricercatori scientifici nell'ambito del progetto "Superfluidity" co-finanziato dalla Comunità Europea, hanno prodotto uno studio, molto originale, pubblicato sulla prestigiosa rivista del settore "Iee communicatios Standard Magazine". Del gruppo fa parte anche un giovane pinerolese, ricercatore presso l'università di Roma Tor Vergata. Si chiama Luca Chiariviglio, nativo di Piossasco, laureato al Politecnico di Torino. Spiega Chiaraviglio: *«Si tratta di un lavoro di ricerca scientific in cui si affronta il tema di portare connettività Internet per mezzo della nuova tecnologia 5G in zone rurali o a basso reddito, garantendo prestazioni molto elevate (molto maggiori rispetto alle attuali tecnologie Lte e Adsl), con un costo per utente contenuto»*. Il risparmio verrebbe ottenuto, tra le altre cose, utilizzando i droni (i noti velivoli radiocomandati di ultima generazione) su cui verrebbero caricate le celle telefoniche necessarie per riflettere il segnale, al posto dei costosi e antiestetici ripetitori fissi, facendoli poi volare dove serve con grande flessibilità. Quello che rende ancora più interessante lo studio per noi pinerolesi è che per tarare nella pratica il progetto è stata presa in considerazione anche l'area compresa tra i Comuni di Piscina, Airasca e Scalenghe. *«Si tratta di una zona rurale a bassa densità abitativa, che conta circa 10.000 abitanti distribuiti su 56 chilometri quadrati, con il nostro sistema che prevede anche risparmi energetici grazie allo sfruttamento dell'energia solare, potremmo portare una connessione a 100 Mbps facendo pagare un abbonamento di 11 euro al mese»* - conclude Chiaraviglio.

**A.M.**

**Luca Chiariviglio.**

And an interview made by Prof. Jairo on Radio NZ here:

http://www.radionz.co.nz/audio/player?audio_id=201849174

# Challenges

## Design/Redesign of Novel/Traditional

- Network Engineering Techniques:
  - Definition: Move resources where the traffic will be offered to the network.
  - Goal: Engineering/Re-engineering terrestrial/airborne networks to optimize the hybrid network: a multi-objective optimization problem with competing objectives in terms of topology, frequency band, resources.
- Traffic Engineering Techniques:
  - Definition: Moving the traffic offered to the network where resources are available.
  - Goal: Engineering/Re-engineering the terrestrial traffic to optimize the overall data delivery of the traffic from sensing locations to processing places: Another multi-objective optimization problem with competing objectives in terms of topology control (shallow versus deep collection trees).

# Challenges

## Design/Redesign of Novel/Traditional

- Data Ferrying Techniques:
  - Routing traffic from collection points to delivery/processing points.
  - Goal: Design novel data ferrying techniques to optimize the overall hybrid network service delivery. E.g. revisit models on collection points can impact service delivery: early visit impact on airborne sensor network lifetime and late visit impact on terrestrial network data piling on sinks (big data)

# Outline

1. Network Engineering
   - Background
   - NE Process

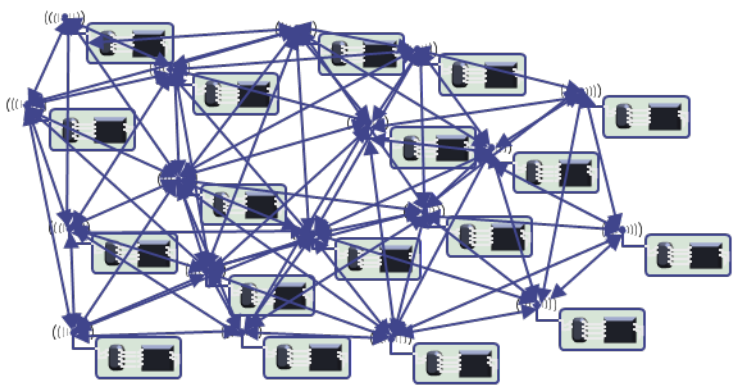
2. Sparse Flat Network
   - NE Problem
   - Algorithmic solution

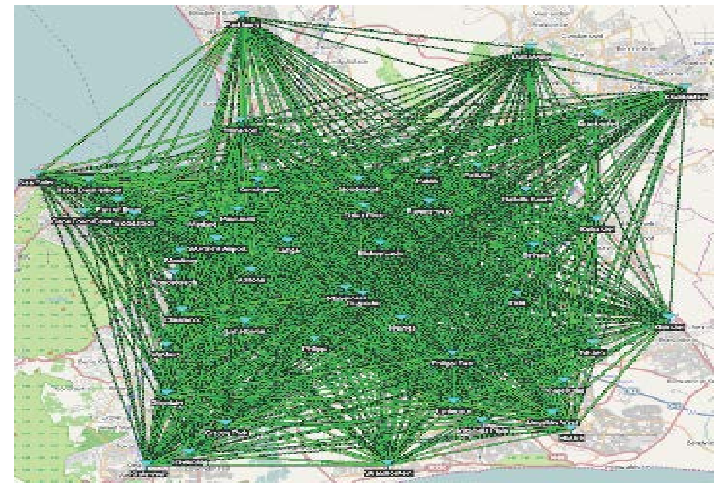
3. Backbone Network
   - NE Problem
   - Algorithmic solution

4. Summary

# Background: Dense networks

- In a very dense networks, too many nodes might be in range for an efficient operation

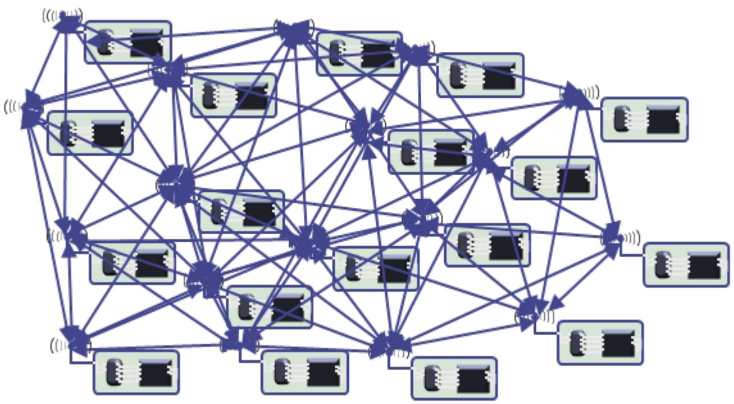




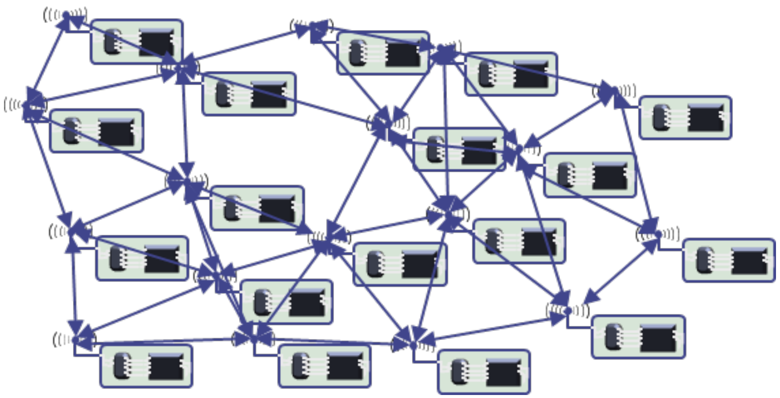
- In a wireless network, a big broadcast domain may be formed leading to
  - Too many collisions,
  - Too complex operation for a MAC protocol,
  - Too many paths to chose from for a routing protocol,
  - And many other issues …

# Background: Sparse networks

- Solution: Make ***topology*** less complex by building a sparse network from the dense network.



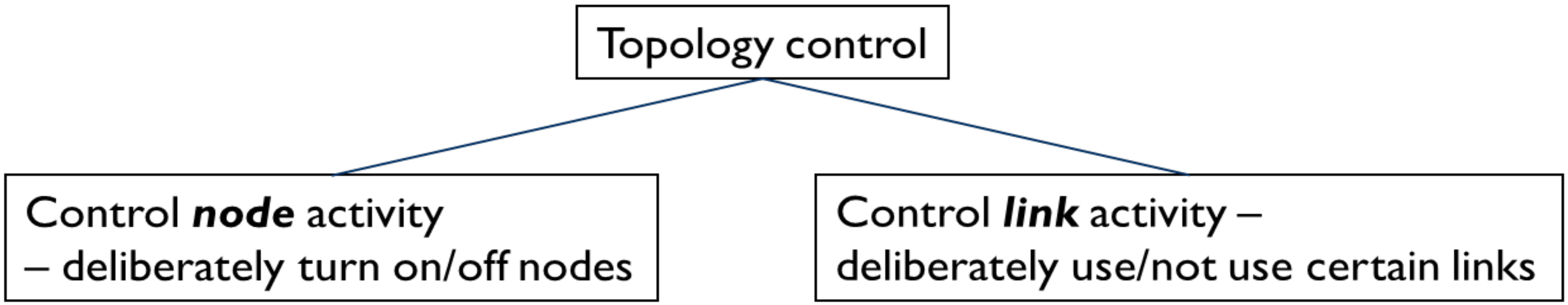
Dense network

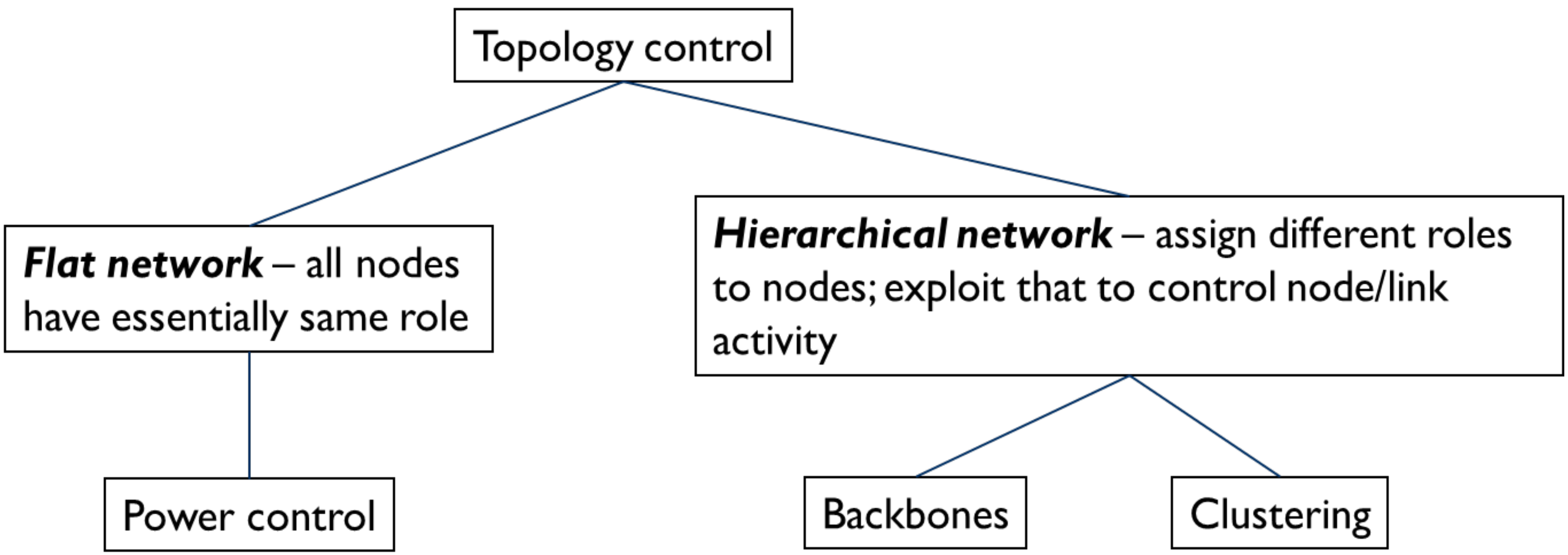


Sparse network

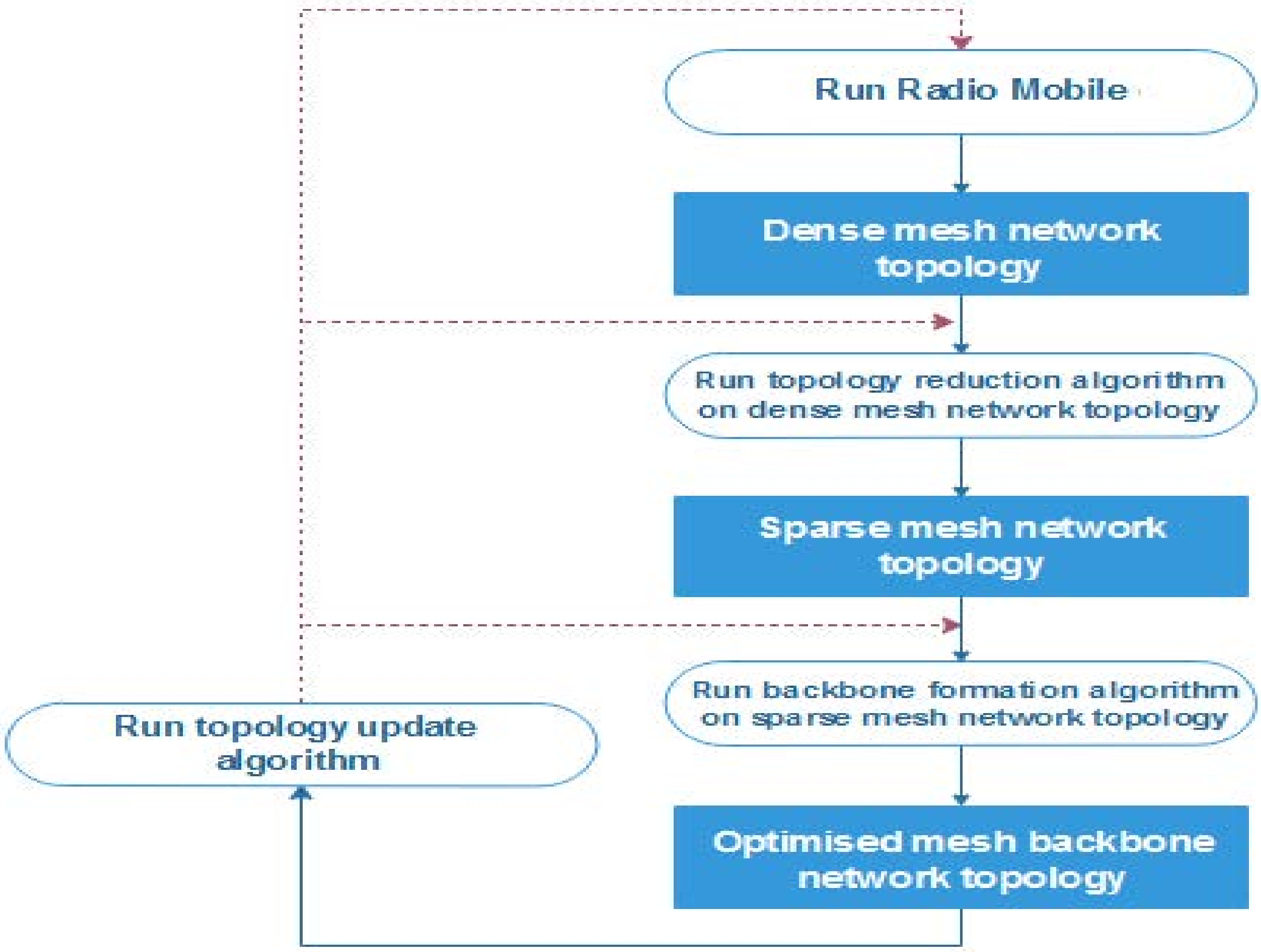
  - *Use **Topology control** to decide* which node is able/allowed to communicate with which other nodes.
  - Topology control needs to meet some constraints: e.g
    - Quality of Service (QoS) in terms of minim/average link margin
    - Reliability/connectivity in terms of path multiplicity

# Background: Topology control options

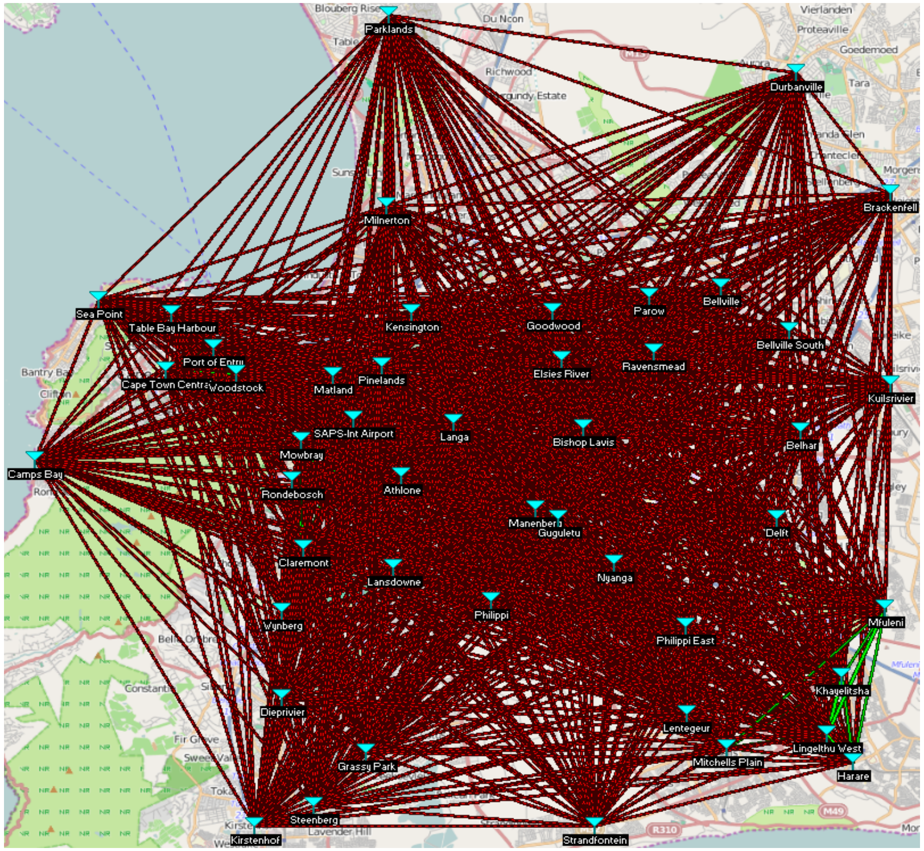


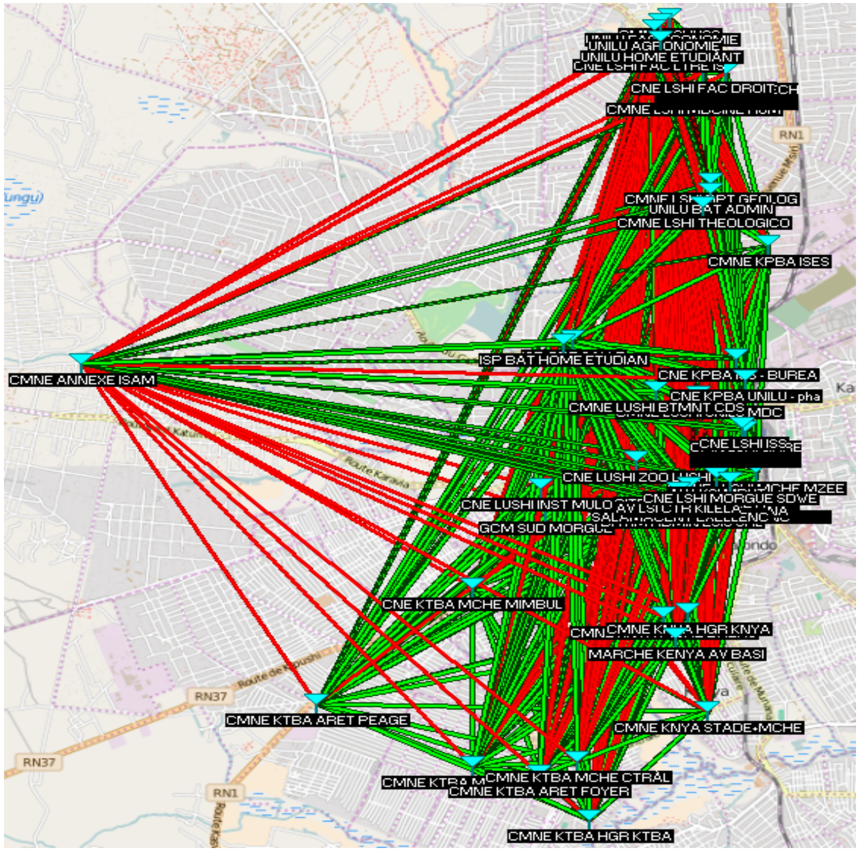
# Network Engineering Process



# Rendered Network Topologies: WiFi

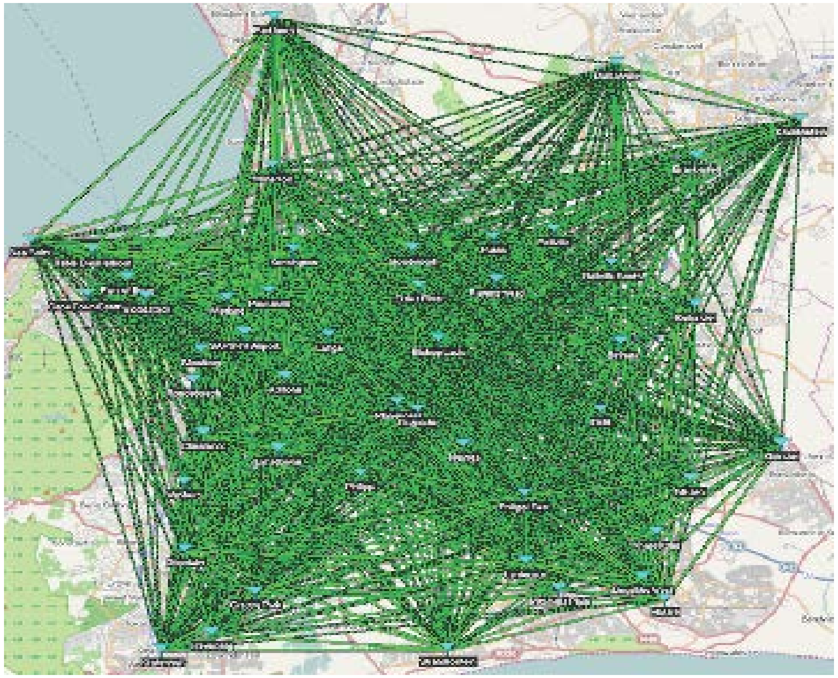


Cape Town WiFi Network

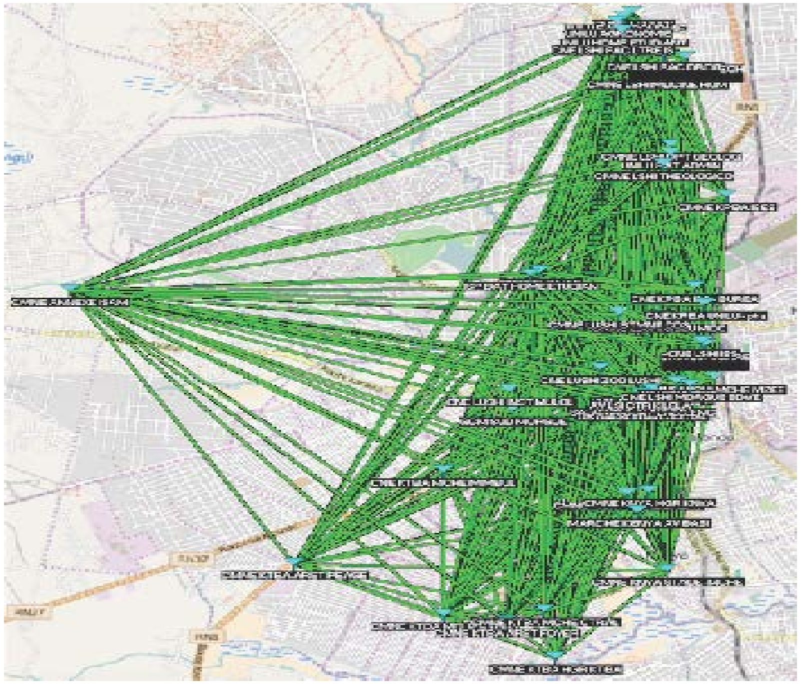


Lubumbashi WiFi Network

# Rendered Network Topologies: WS



Cape Town White Space Network



Lubumbashi  White Space  Network

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# Sparse Flat Network Problem

$$\hat{\tau}_{opt}(\mathcal{C}_{opt}) = \max_{\mathcal{C}_n \in \mathcal{G}} \sum_{k \in \mathbb{N}[\mathcal{C}_n]} P(k)$$

Subject to

**(14.1)** $\tau_{lm}(x, y) > \tau_{lm} \quad \forall \quad x, y \in \mathcal{C}_{opt}$

**(14.2)** $k_{sp}(x, y) > \tau_{sp} \quad \forall \quad x, y \in \mathcal{C}_{opt}$

where $\mathbb{N}(X)$ is the set of nodes in the configuration $X$. Note that constraints 14.1 and 14.2 express the QoS in terms of link margin and reliability respectively.

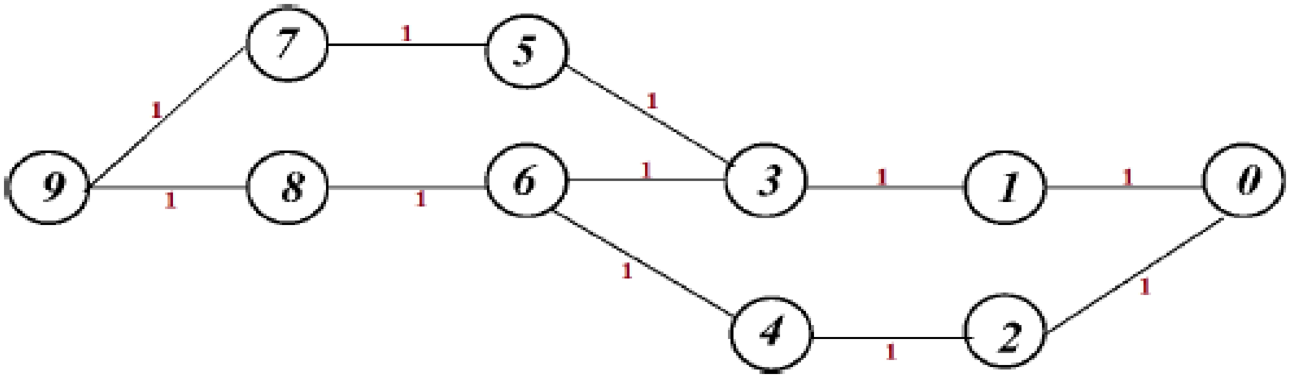
# Algorithmic Solution

- Link-based Topology Reduction

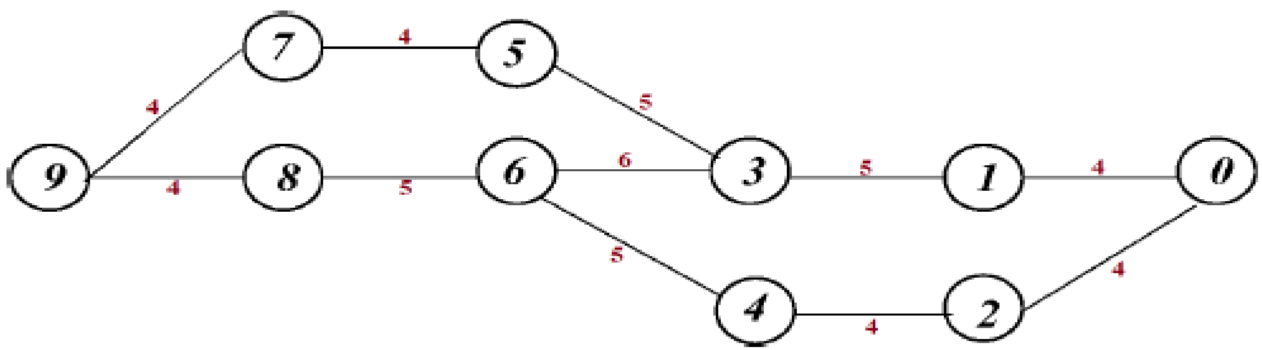
**Algorithm 1:** LTR algorithm

```
mark all links in dense mesh network as non-visited;
for each non-visited link of the network do
    select worst non-visited link of the network; // i.e. link with lowest
        link margin.
    artificially delete the link;
    run the K-shortest path to detect if the network is still k-connected; // it
        is k-connected if you can find k-disjoint shortest paths for
        each source-destination pair of the reduced network.
    if it is k-connected then
        remove the link permanently;
    else
        leave the link and mark it as visited;
end
```

# K-Shortest Path Algorithmic




(a) Trap Network Topology




(b) Over-subscribed Trap Topology

# K-Shortest Path Algorithmic

**Step 1. Link weight over-subscription.** Adjust the link weights

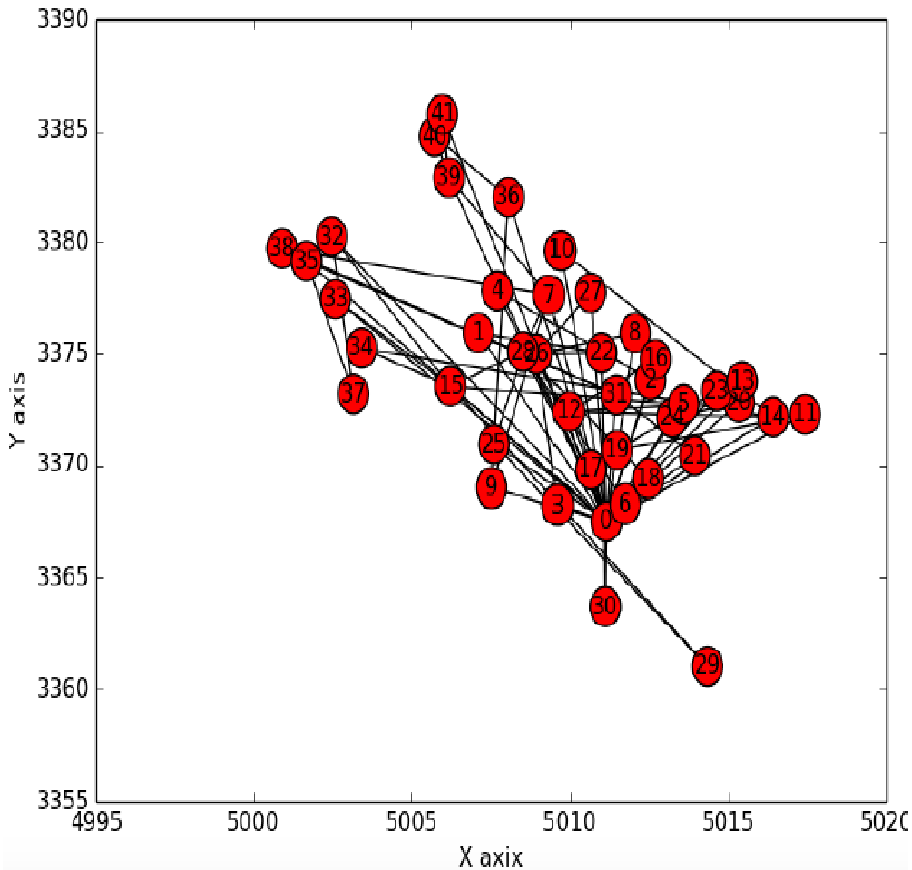
For each link $l \in L$, set $w(l) = w(l) + ds(l) + dd(l)$ where

- $w(l)$ is the weight on link l
- $ds(l)$ is the node density of the source node on link l
- $dd(l)$ is the node density of destination node on link l.

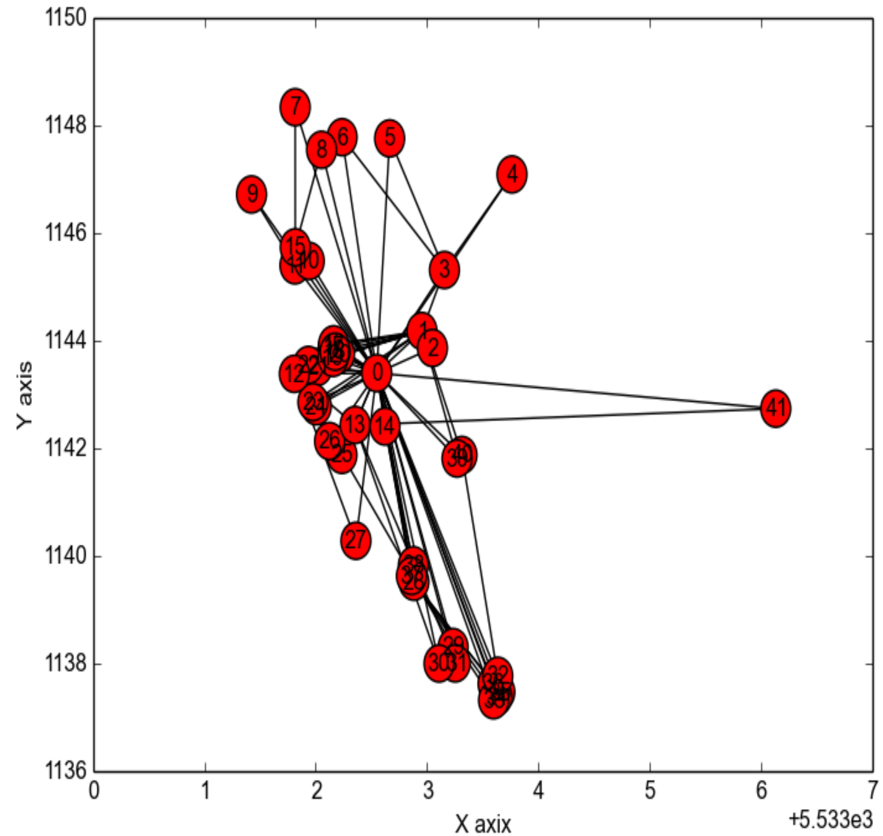
**Step 2. Disjoint paths computation.**
For each source,destination pair $(S,D)$

- *path finding*: Find a shortest path $p$ between $S$ and $D$
- *network pruning*: Prune the links of $p$ from the network topology T
- Stopping condition: If T is disconnected
  then *Exit*
  else set $K(S,D)=K(S,D) + p$

# Algorithmic Solution

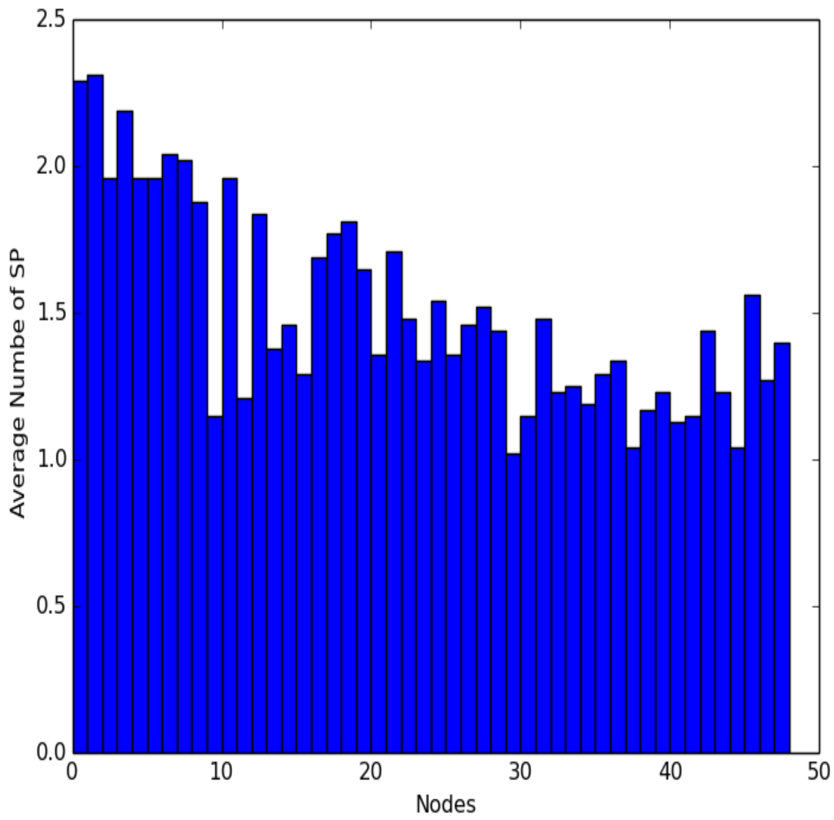



Cape Town Sparse Network

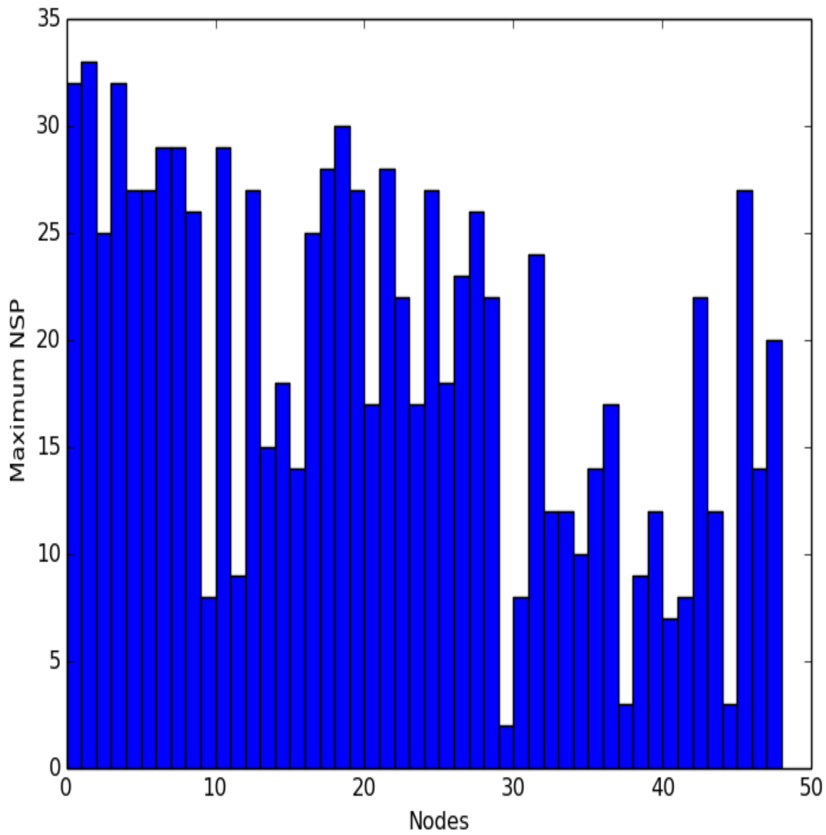



Lubumbashi Sparse Network

# Fault-tolerance: Cape Town Network




Average Number of Disjoint Shortest Paths




Maximum Number of Disjoint Shortest Paths

# Algorithmic Solution

- Preliminary Results

Table 1: Backbone network topology vs sparse network topology

| Network performance | Sparse network | Backbone |
|---|---|---|
| Node degree | 3.81 | 4.03 |
| Coefficient of variation (link margin-(dBm)) | 2.83 | 3.86 |
| Shortest distance (km) | 12.88 | 12.31 |
| Path multiplicity | 2 | 1 |

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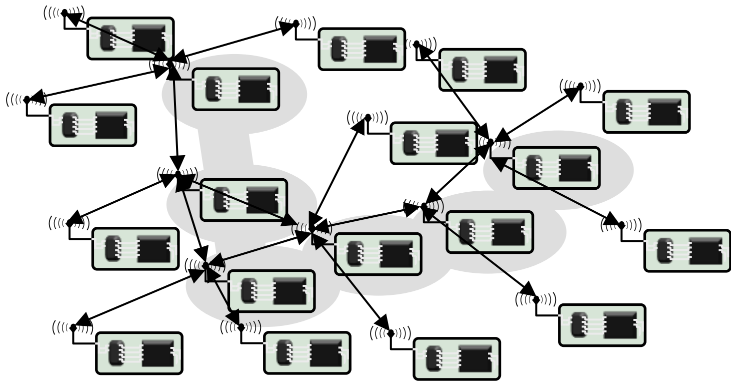
# Hierarchical networks: backbone

- Construct a ***backbone*** network
  - Some nodes "control" their neighbors – they form a (minimal) ***dominating set***
  - Each node should have a  controlling neighbor



  - Controlling nodes have to be connected (backbone)
  - Only links within backbone and from backbone to controlled neighbors are used
- Formally: Given graph G=(V,E), construct D ∊ V such that

$$\forall v \in V : v \in D \vee \exists d \in D : (v,d) \in E$$

# Backbone NE Problem

$$\hat{\tau}_{opt}(\mathcal{C}_{opt}) = \max_{\mathcal{C}_n \in \mathcal{G}} \sum_{k \in \mathbb{N}[\mathcal{C}_n]} P(k)$$

Subject to

$\mathbf{(15.1)}$ $l_{mg}(x, y) > \tau_{lm} \ \forall \ x, y \in \mathcal{C}_{opt}$

$\mathbf{(15.2)}$ $k_{sp}(x, y) > \tau_{sp} \ \forall \ x, y \in \mathcal{C}_{opt}$

$\mathbf{(15.3)}$ $\forall n \in \mathcal{C}_{opt} : n \in \hat{\mathcal{N}} \vee \exists m \in \hat{\mathcal{N}} : (n, m) \in \mathcal{L}$

$\mathbf{(15.4)}$ $\hat{\mathcal{N}} \cup \check{\mathcal{N}} = \emptyset \wedge \hat{\mathcal{N}} \cap \check{\mathcal{N}} = \mathcal{N}$

# Backbone Reward Functions

- Topology Aware Reward Function

$$P_t(\mathcal{G}) = \sum_{i \in \mathcal{N}} P_t(i) \tag{2}$$

$$P_t(i) = \alpha * Dc_i + \beta * Ccn_i + \gamma * Cc_i \tag{3}$$

- White Space Aware Reward Function

$$P_w(\mathcal{G}) = \sum_{i \in \mathcal{N}} P_w(i) \tag{8}$$

$$P_w(i) = \alpha_w * QTY_i + \beta_w * QLY_i + \gamma_w * DVY_i + \theta_w * WUS_i \tag{9}$$

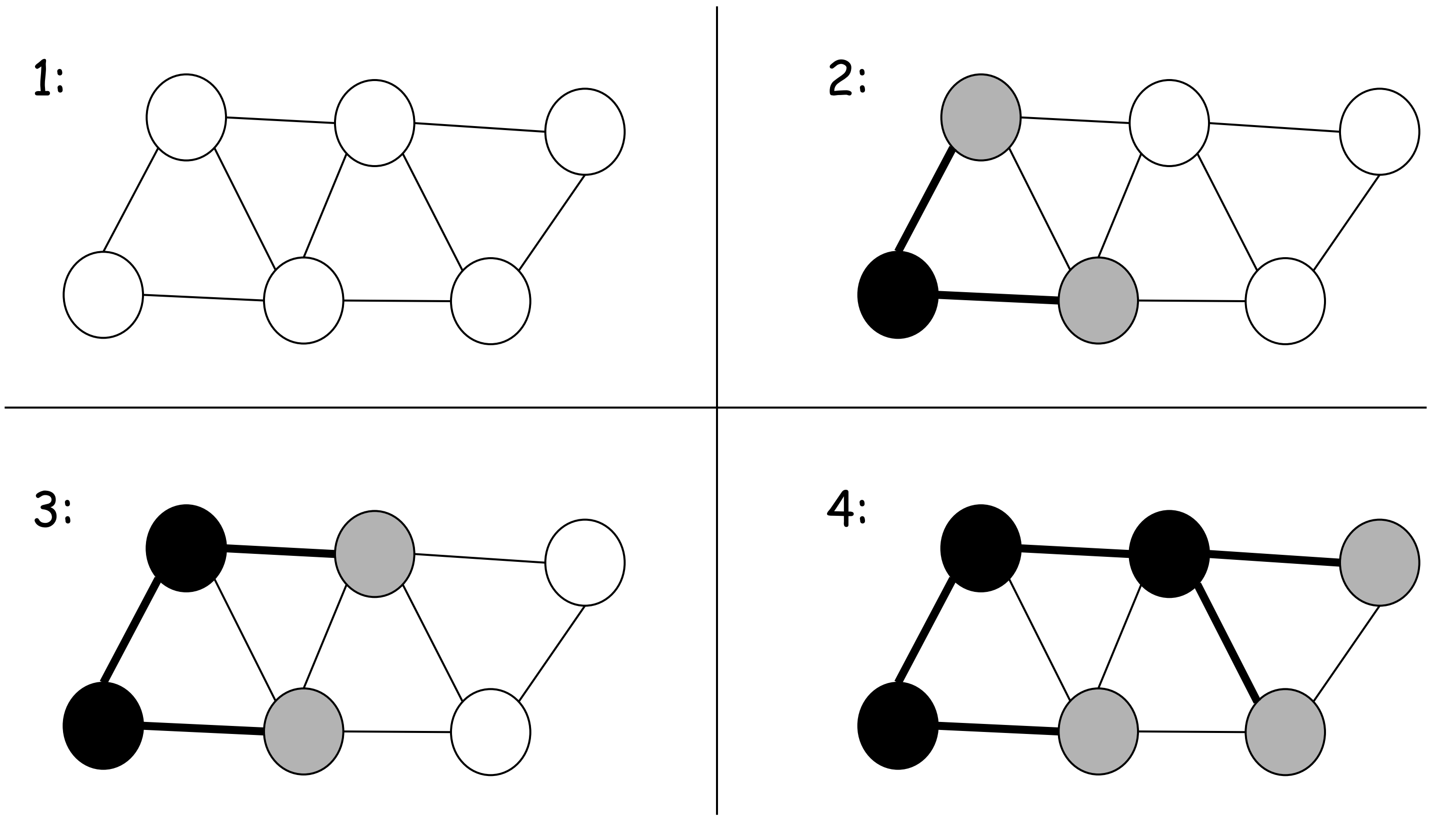
# Hierarchical networks – backbones

- Idea: Select some nodes from the network/graph to form a ***backbone***
  - A connected, minimal, dominating set (MDS or MCDS)
  - Dominating nodes control their neighbors
  - Protocols like routing are confronted with a simple topology – from a simple node, route to the backbone, routing in backbone is simple (few nodes)
- Problem: MDS is an NP-hard problem
  - Hard to approximate, and even approximations need quite a few messages

# Backbone by growing a tree

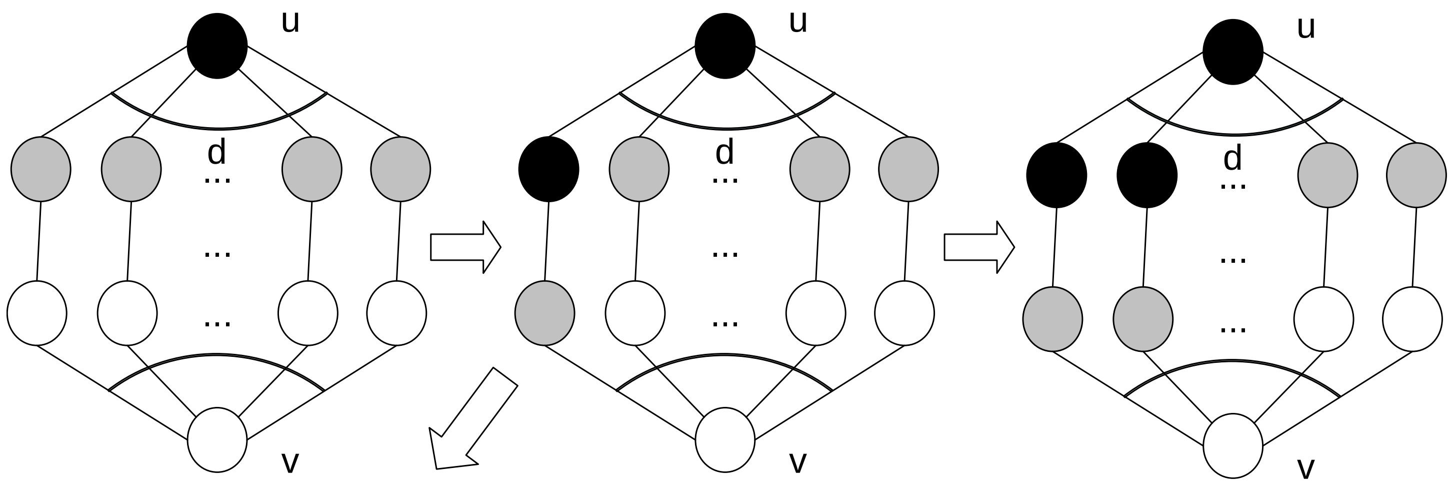
```
initialize all nodes' color to white
pick an arbitrary node and color it grey

while (there are white nodes) {
  pick a grey node v that has white neighbors
  color the grey node v black
  foreach white neighbor u of v {
    color u grey
    add (v,u) to tree T
  }
}
```

# Backbone by growing a tree: Example

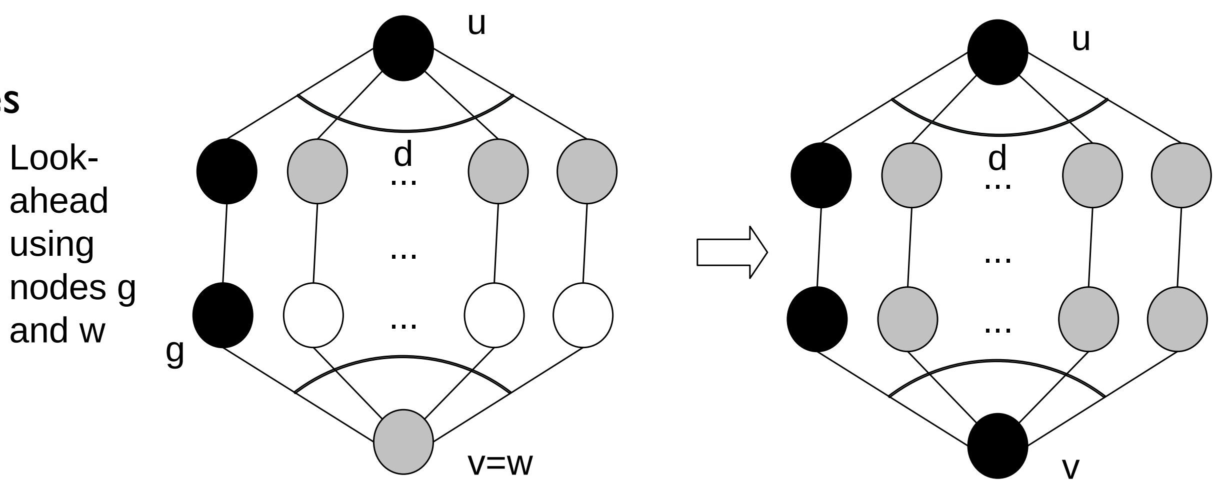


# Problem: Which gray node to pick?

- When blindly picking any gray node to turn black, resulting tree can be very bad




Solution:
Look ahead!
One step suffices



# Backbone Algorithmic Solution

- Graph Coloring Algorithm

**Algorithm 2:** Backbone formation

1. Initialisation.

   Assign a white colour and zero height to all nodes of the network,

   Select a node $n$ from $White$ whose profit/reward is highest,

   $Backbone \leftarrow \{n\}$,

   $Grey \leftarrow$ all neighbours of $n$,

   $White \leftarrow N \setminus (\{n\} \cup Grey)$.

2. Select a node $k$ from $Grey$ whose profit/reward is highest and height is lower.

   Include $k$ into the $Backbone$,

   Assign a black color to $k$ and update its height,

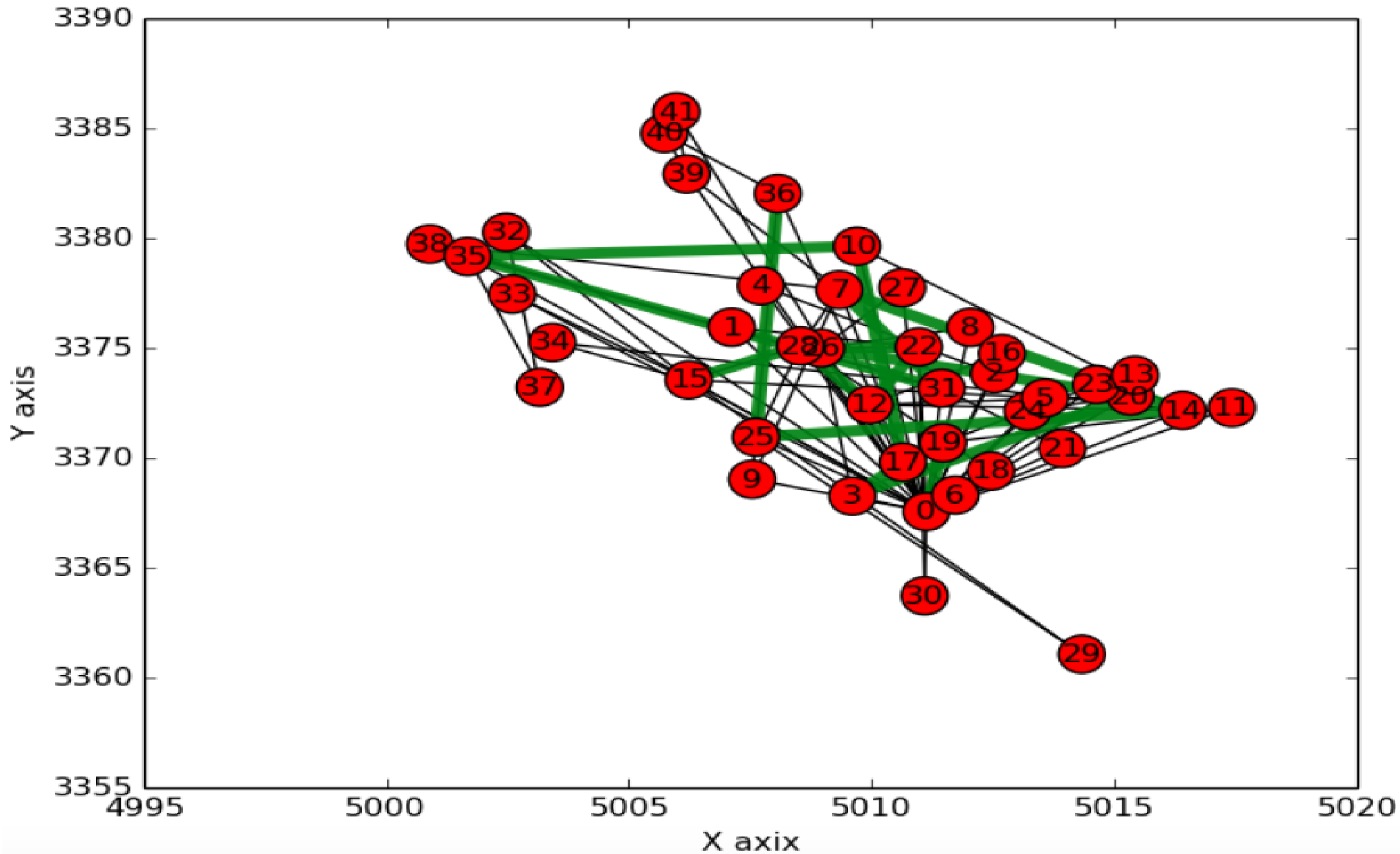
   Remove $k$ and its neighbours from $White$,

   Include the neighbours of $k$ in $Grey$.

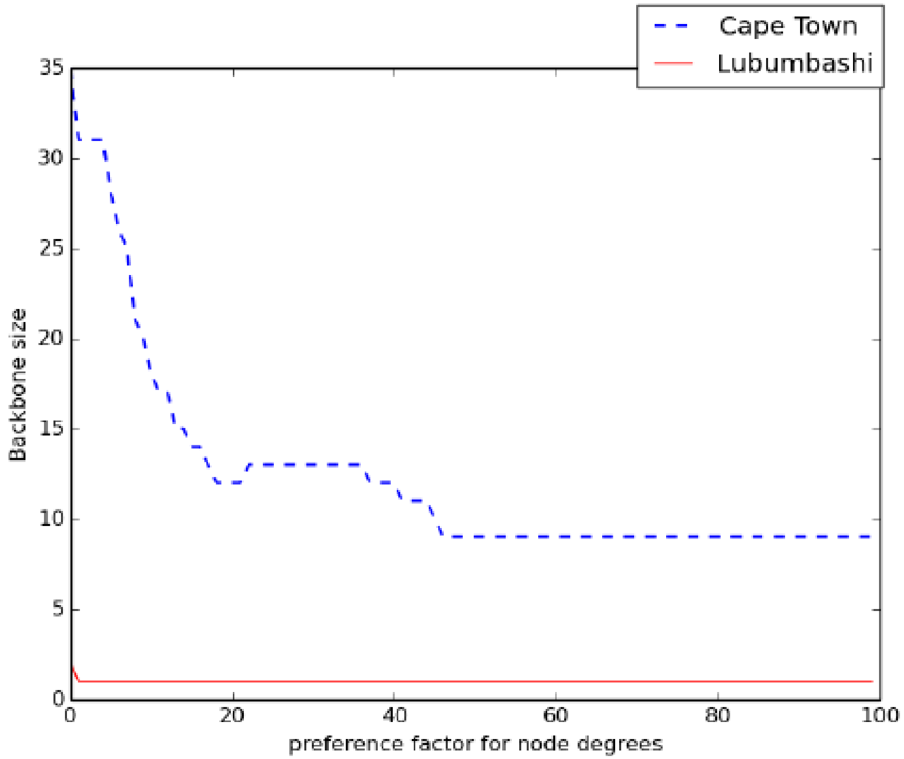
3. Repeat Step 2 whenever $White \neq \emptyset$.

Note: the height of grey nodes may be lower or higher depending on your definition.

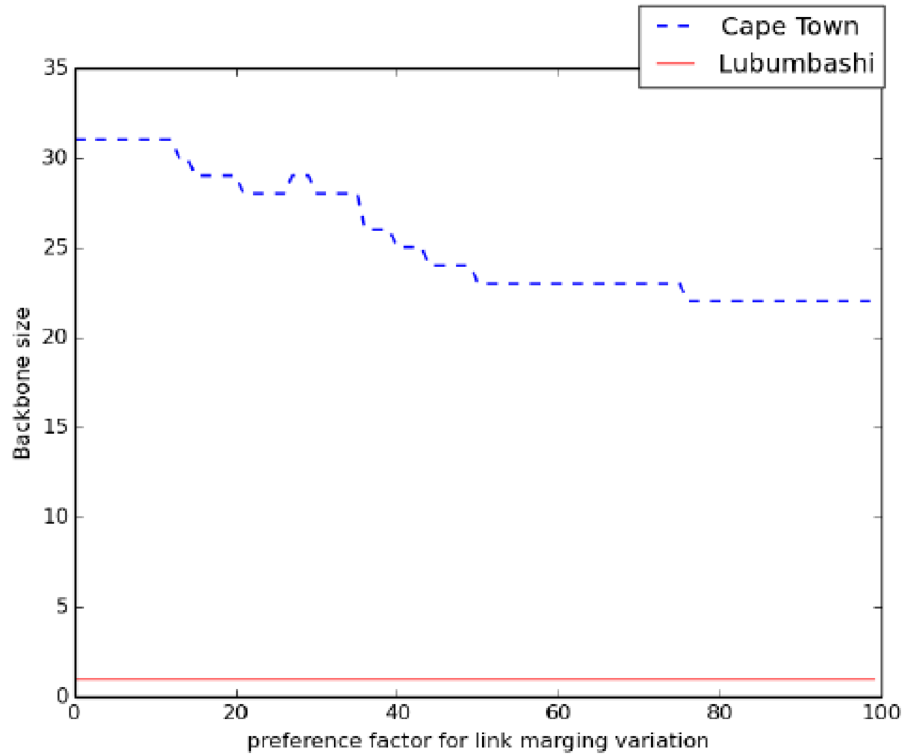
# Rendered Backbone Network



# Impact of Design Parameters

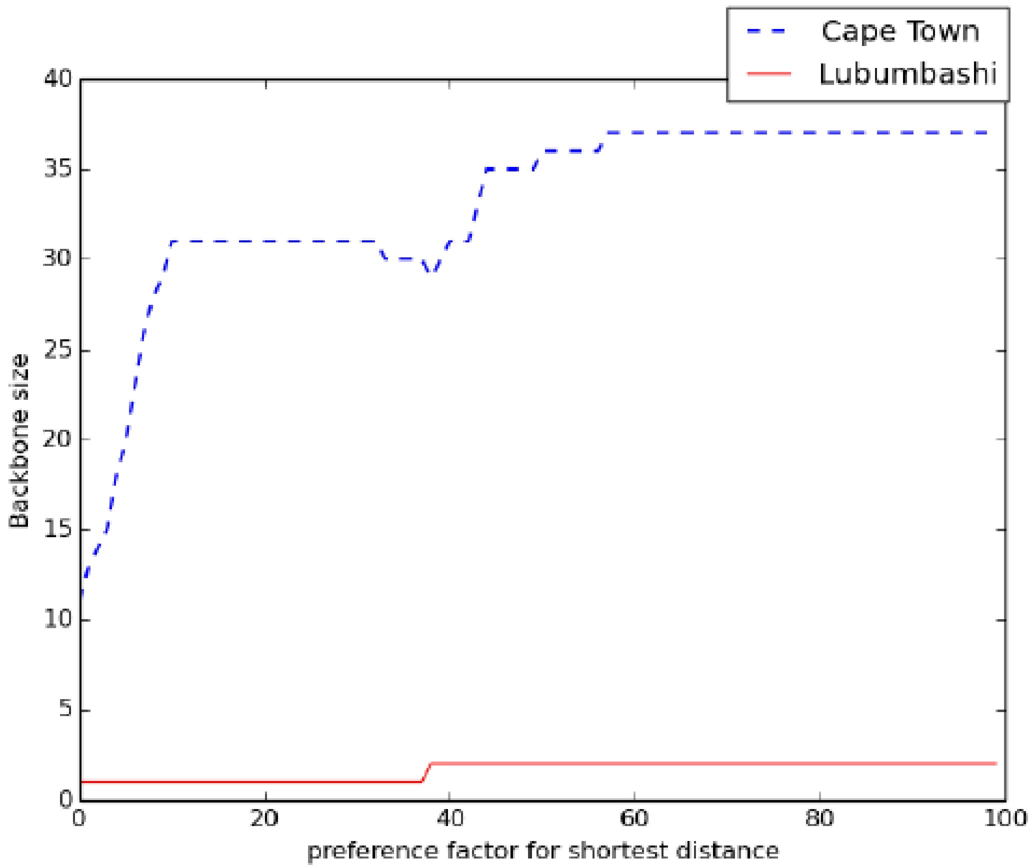



Impact of *alpha* on backbone size



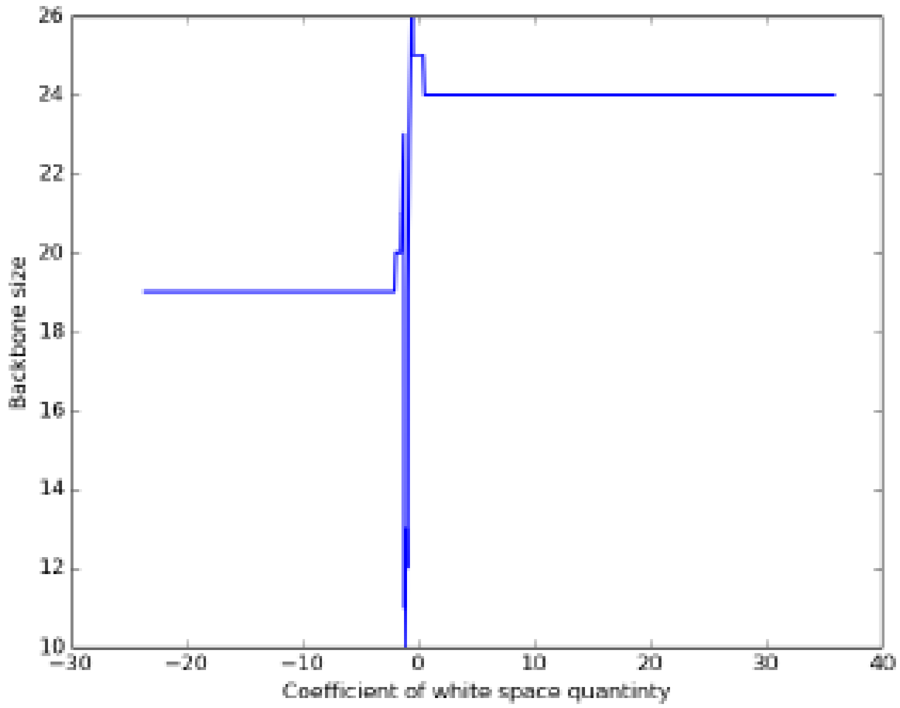

Impact of *beta* on backbone size

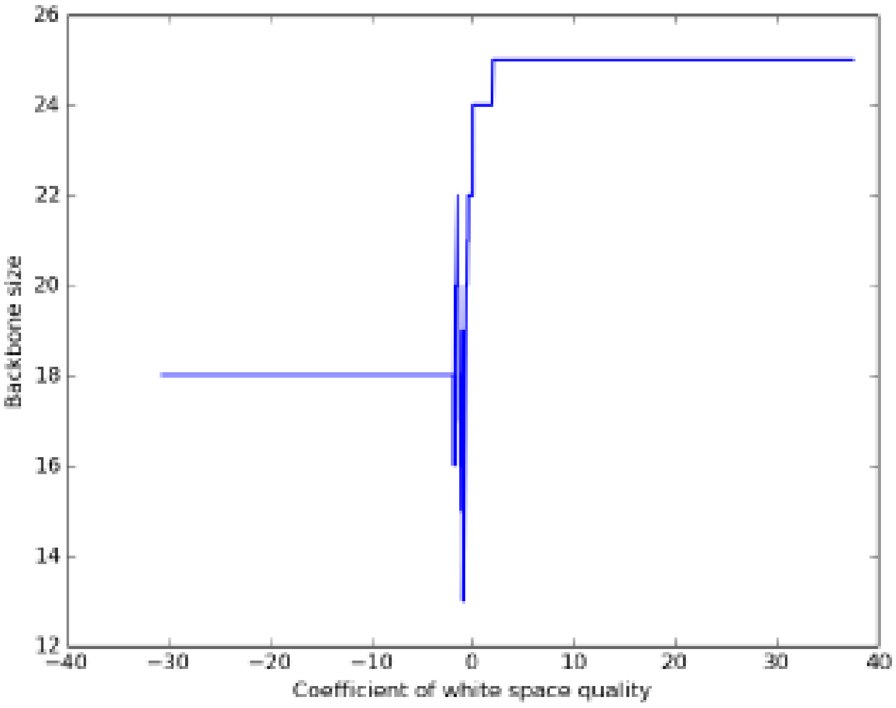
# Impact of Design Parameters




Impact of *lambda* on backbone size

# Impact of Design Parameters

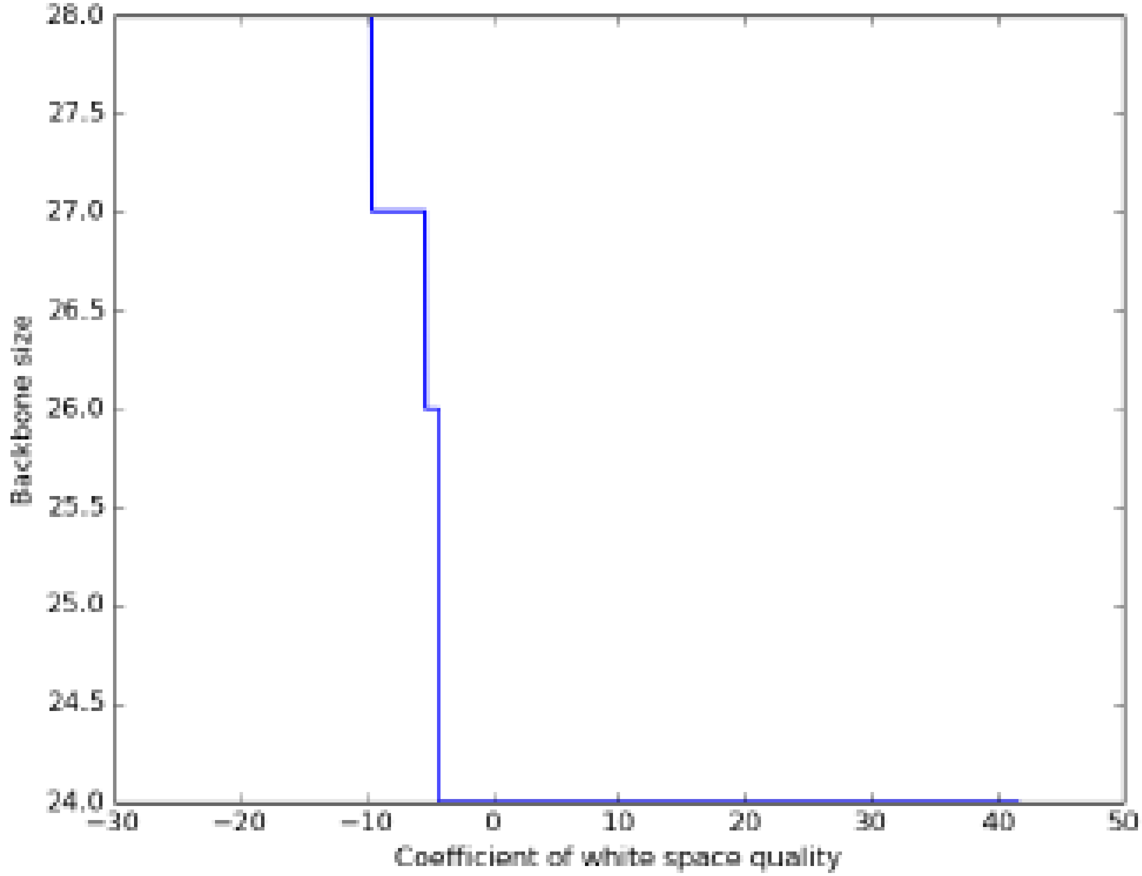



Impact of *coefficient of white space quantity*

Impact of coefficient of white space quality

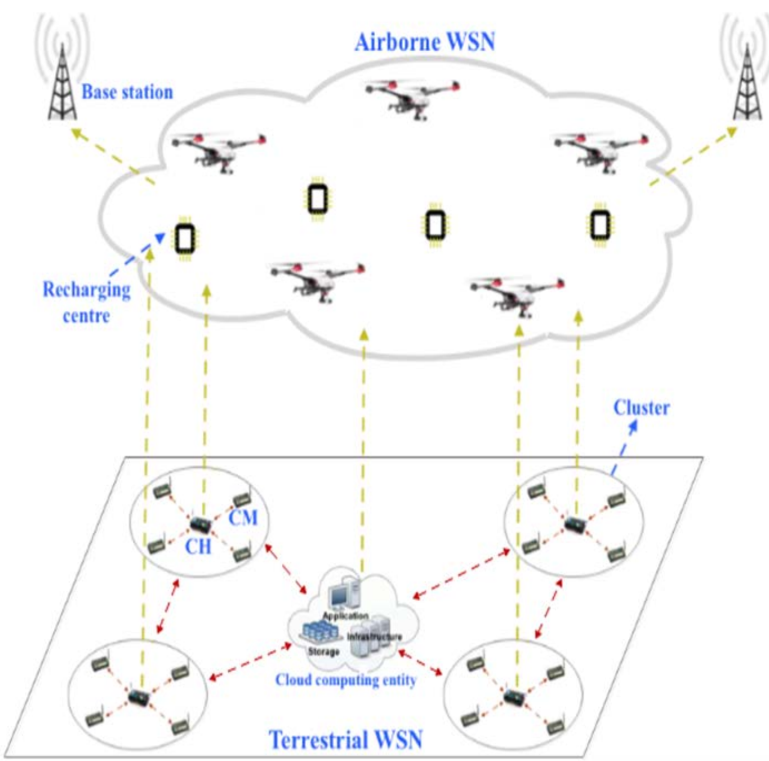
# Impact of Design Parameters

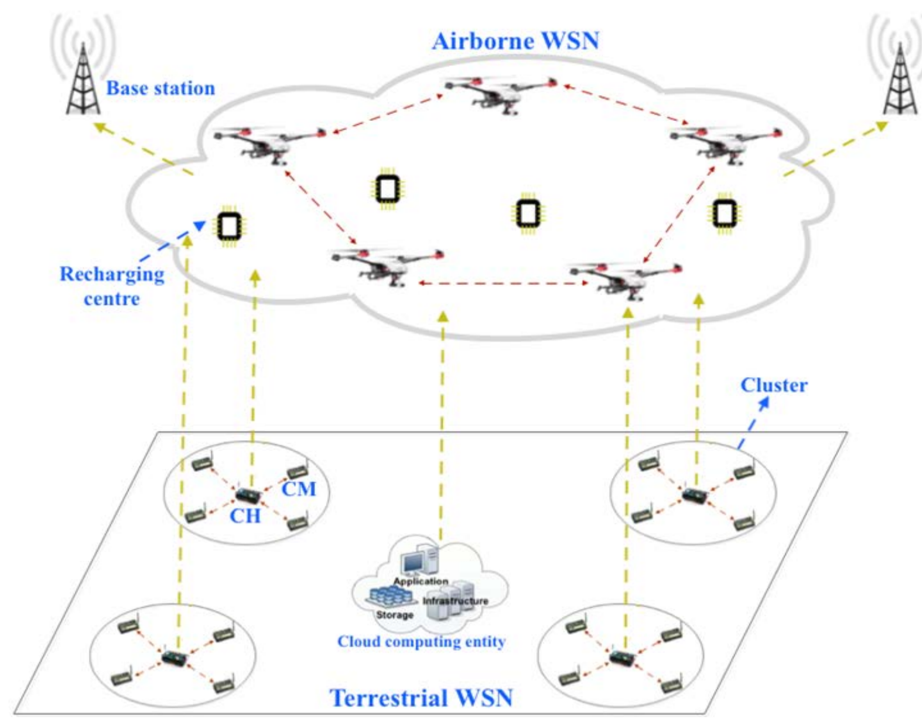



Impact of coefficient of *white space diversity*

# What is the best NE option ??

1. Bigger vs Smaller Backbone ??
2. Airborne vs Terrestrial Mesh ??
3. WiFi vs White Space Frequency ??



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# Summary

We have introduced some of the fundamental concepts behind the Internet-of-Things networks engineering with their applications to the developing world by looking at

- Emerging IoT network architectures
- Some deployment scenarios
- IoT network engineering techniques

These architectures and techniques have been tested in Testbed research networks. These techniques need to be integrated in Open Source/Access tools such as SLAT/Telegram to increase their accessibility and wide extension of hybrid IoT networks.